INDUSTRIAL HYGIENE AND TOXICOLOGY

SECOND REVISED EDITION

VOLUME I

GENERAL PRINCIPLES

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Industrial hygie..

giene

② human engineering
③ Industrial safety
④ Industrial sanitation
⑤ toxic materials ⑥ contaminants ⑦ Air cleaning
⑧ ventilation ⑨ respirators
⑩ Dust ⑪ Air pollution
⑫ occupational diseases
⑬ fire hazards ⑭ explosion hazards ~~hazards~~
⑮ explosives ⑯ Combustibles
⑰ Abnormal atmospheric pressure
⑱ Industrial noise
⑲ Sound ⑳ Radiations
㉑ Lighting
㉒ heat control
㉓ hot industries

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65.	7/2/61	2-11-61
296.	28/11	
67	26/12/61	3/1
411.	1/8	2/7/62
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INDUSTRIAL HYGIENE AND TOXICOLOGY

Second Revised Edition *In Three Volumes*

VOLUME I:
General Principles

VOLUME II:
Toxicology

VOLUME III:
Industrial Environmental Analysis

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INDUSTRIAL HYGIENE AND TOXICOLOGY

Second Revised Edition

FRANK A. PATTY, *Editor*

VOLUME I

GENERAL PRINCIPLES

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Industrial hygie

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PREFACE

to the Second Edition, Volume I

Major changes in emphasis in this revision are found in the subjects of Noise, Heat, Ionizing Radiation, Human Engineering and Industrial Safety, Sanitation, Air Pollution, and Illumination.

Noise and its environmental implications have assumed a degree of importance that warrants a chapter devoted exclusively to the subject.

Heat and its control have received much attention in industrial hygiene circles in recent years, and technology concerning the conditioning of air for health and comfort is much in demand. The subject is of sufficient importance to warrant four chapters dealing with the various phases of the problem, including Air Conditioning, Air Cleaning, Ventilation, and Heat Control in the Hot Industries.

With the rapidly growing application of radioisotopes and the peacetime uses of nuclear power, the recognition, evaluation, and control of *ionizing radiation* exposures and the inhalation and ingestion of radioactive gases and aerosols assume industrial importance comparable to those of other highly hazardous environmental contaminants. Industrial hygienists will find it increasingly necessary to acquire a working knowledge in radiation hygiene. Health physicists as they enter industrial work environments will find it increasingly necessary to recognize the health problems attending other physical forces—such as sound, heat, and light—chemical contaminants, and all the harmful environmental situations with which industrial employees may come in contact. Natural and irresistible forces work against clannishness and toward efficient and expedient methods of competently protecting the employees' health and safety.

Human Engineering and Industrial Safety. To develop the best possible adjustment between man and his job is a fringe interest because methods engineering and machine design must take into account certain engineering, biological, and environmental facts commonplace to the industrial hygiene discipline.

Industrial Sanitation, another fringe interest, deals with problems not inherent in the manufacturing process and needs to be drawn into sharper focus defining its relation to the field of health engineering and, therefore, a chapter to this end has been included.

Air Pollution involves industrial hygiene because the contaminants in the air of the community are the base line upon which any indoor contamination studies or control programs must be built. In many cases pollutants must be removed from air before admitting it to the plant environment. Likewise, stack effluents frequently require cleaning up before they are acceptable to the community atmosphere. Much technology is common to both the indoor and outdoor air contamination problems.

A separate chapter is devoted to the subject of *Illumination,* a controversial field not heretofore sufficiently explored by industrial hygienists.

The objective of industrial hygiene remains the same—safeguarding the health of working people and improving work environments.

FRANK A. PATTY

February, 1958

PREFACE

to the First Edition, Volume I

Industrial hygiene has been recognized and practiced from the time of Pliny down through the ages. It is the present concept of industrial hygiene that is relatively new—the concept of anticipating and recognizing potentially harmful situations and applying engineering control measures before serious injury results. There are some who question industry's ability to control all harmful exposures; and there is quite naturally a tendency to take the easy way out of a difficulty by substituting materials of low or moderate toxicity for those of a hazardous nature. Nevertheless, where incentives such as low cost, availability, or superior properties of a hazardous material justify the provision of positive engineering controls, they can be supplied promptly.

It is said that artisans are born rather than made, but there can be no doubt that industrial hygienists must be made, and it takes years to mellow some of us with sufficient understanding so that we can use our knowledge of the basic principles of industrial hygiene to the best advantage in accomplishing our goal.

Depending somewhat upon where we acquire our academic training and initial experience in field work, we are likely to start out with the concept that industry has one purpose—to make money—and that, in following that urge, the humanitarian aspects are apt to be neglected. So it is with somewhat of a shock that some of us learn that many industries are eagerly taking the initiative in improving the work environment of their employees. Our first ideas of introducing hygiene to industry are likely to involve some means of maneuvering into a position in which our recommendations for control measures are to be accepted as commandments not to be questioned and not, upon penalty of closing up shop, to be ignored. It is only gradually that we become aware of the fact that in promoting anything to the American public a sound idea "takes" more quickly and develops faster if it is "sold" rather than presented as an ultimatum. As a people we basically resent being told bluntly that we have to do a thing: we much prefer to "discover" for ourselves that the proposed new course is correct and therefore to our advantage. Adams* expresses these ideas well in his recent book, from which I quote:

> The American is a composite of almost all races, nationalities, and classes . . . He hates a bit and bridle as heartily as does a young colt . . . There *are* dirty politicians, dirty labor leaders, dirty business men—black markets, some selfish and dirty consumers—but Americans, now 138,000,000 of them, *the American people,* are the hope of the world and of the whole future of humanity.

* J. T. Adams, *Big Business in Democracy*. Scribner's, New York, 1946.

The industrial hygienist becomes aware that salesmanship is a necessary part of his practice. The salesman will think of the "buyer's" point of view and, first of all, develop his recommendations for environmental controls with the understanding of an economist, and then stress all the advantages. He will simplify his work by taking advantage of the views of production engineers and occasionally going them one better by saving them money in the conservation of materials or in the recovery of a by-product. One cardinal rule he learns early is not to "bluff" or try to impress his audience with his superior knowledge. Some few persons have the ability to "get away with it," but the odds are against them and it is much safer to work on the same plane as our audience whether that means a step down or a jump up, and it helps to imagine one's self in the position of the man one is trying to influence.

Industrial hygiene may be defined as *the science and art of preserving health through the recognition, evaluation, and control of environmental causes and sources of illness in industry*. It resolves itself into the problem of finding factors or conditions in workplaces that may cause or contribute to the illness or serious discomfort of employees, and of devising methods and means of eliminating or controlling such conditions.

It would be a mistake to attempt to give the impression that industrial hygiene is pure science, or that it is restricted to the art of applying scientific principles: much of it involves a liberal use of common sense or what is perhaps better known as "horse sense." The job will never become monotonous or routine because the chemist, the engineer, and the physicist will keep introducing new and more or less hazardous materials and processes that require new developments for the evaluation and control of exposures attendant to their use. Neither is the job glamorous or spectacular, and much of it is hard work bordering on drudgery, but it has its compensations.

> I should like to narrate an incident that, because of its fundamentality and at the same time dramatic departure from the daily routine of an industrial hygienist, may be worth describing without retouching. One of the pioneers in industrial medicine and hygiene whom most readers will recognize without further identification might have regarded this incident as an "acorn."* However, since no tangible reward or token of appreciation was either anticipated or received and the only special remuneration was the feeling of satisfaction that goes with accomplishing any job, assumed or assigned, it was considered all in the day's work.
>
> While busily engaged at my office one morning in the industrial hygienist's favorite occupation of pouring over survey reports, I received a telephone call: "This is Dr. ——, chemist over at —— Dry Dock. Here's something I think you should know about and maybe you will want to come over and look around. We just sent a man to the hospital and we have two more who are laid up and in a serious condition. The —— was docked here just two weeks ago for repairs and conversion and out of the 2,000 men working on her, over 100 are affected with some sort of breaking out and itch and all the men are threatening to quit if we don't find out what's wrong and correct it. The boat's been in the tropics for some time and the workmen fear some tropical disease is responsible for this outbreak."

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* C. P. McCord, *A Blind Hog's Acorns*, Cloud, Inc., Chicago, 1945.

Yes, I did want to look around, and within an hour was aboard the ship and observed many of the afflicted men at work. There was considerable grumbling and an abundance of dirty looks. Several men wore bandages over vesicular patches and on a few there was evidence of a generalized fine vesiculation. We went through the ship from stem to stern and forecastle to bilge. It was like a beehive: men were cutting with torches, sawing out panels, knocking off plaster, shoveling out debris and filth, scrubbing, and removing the interior furnishings preparatory to refitting the boat completely. Admittedly the ship was dirty—in fact, in some areas it was filthy—but so what! Next we went to the first-aid room to see the attendant and find out what, if any, information could be obtained there. The place was crowded with patients, and while we waited to see the attendant first-aid man we could hear the grumblings of the waiting patients, who complained of "filthy working conditions" and that, if the health department were not called in to condemn the place, everyone should quit before they became ill—that the place was "infested with fleas" and that they didn't "want any tropical fevers." Finally the harassed attendant came to us, but he had little to offer except to comment that the cases and complaints were getting more numerous and that he certainly hoped we could do something.

We had seen the situation: a once luxuriant ship, somewhat filthy in spots, an explosive outbreak of dermatitis in nearly ten per cent of the 2,000 men at work on the ship, no reported cases among the many thousands of workmen in adjacent areas of the same shipyard, and, unless something were done quickly, work on this desperately needed troop ship and possibly in the entire yard would stop.

The job looked interesting if not easy. We collected samples of everything we could get loose—plaster, upholstery, hair stuffing, sweepings, scrapings from panels and floors, and samples of the different woods and sawdusts, and returned to the laboratory. The samples were turned over to the chemists and microscopists to look for fumigants, insecticides, alkalies, and other common irritants, as well as any signs of insects or parasites. Two members of the staff were inveigled into joining me in making patch tests with some of the materials after saturating them with alcohol as a precautionary measure. While these tests were in progress a medical associate told me with an air of finality that our company had called in, as consultant, an authority on dermatology and that he planned to leave the matter entirely in the consultant's hands. When I took the story to my immediate superior he said it was very interesting, and sometime when he had more time I should "tell him all about it." I telephoned the consultant dermatologist and inquired if he had seen the cases and had any ideas of what might cause the difficulty. Yes, he had seen them, and, except for the fact that it didn't make sense, he would say that they resembled poison-ivy cases. That agreed with what we had seen on the job, but we had not seen any poison ivy! After all of the chemical and microscopic tests proved negative except for an insignificant amount of arsenic in the sweepings, there remained only the possibility that the patch tests might indicate an irritant. After 48 hours, and with all patch tests negative, the shipyard's chemist reported that there were several more cases, including an electrician working on the dock beside the boat, and that a walkout seemed imminent even though the ship was desperately needed for a troop transport.

The fact that an electrician who possibly had not been on the boat was affected gave an indication that the problem might be attacked from epidemiological approach by personally interviewing some of the afflicted men. Discussion of personal matters with employees, especially shipyard workers, is ordinarily something to be avoided, but in this instance approval of such interviews was readily obtained from all parties concerned. Aided by the chemist and two safety engineers, we went out on the job and talked to some of the affected men, including the electrician, who had never been on the suspected ship, and a security policeman, who was seriously affected and had been aboard the ship only once for a few minutes. This introduced a strong element of doubt about the ship's

> being the contact source and diverted our attention to other possible sources of irritant material. It developed that nearly all cases were on the day shift. The electrician's case had been diagnosed "cable rash," but, since the characteristics of his lesions were similar to those of the other workmen, we did not waste time examining the cables with which he had been working. Instead, we investigated all the possible exposure sources where the men spent their time when they were off the ship: where they ate their lunch, where they loafed, and the route they took to and from work. We found what appeared to be some damaged oil drums in a pile on a sand lot where several men had spent their lunch hour within the shipyard grounds, but about a block away from the dock to which the boat was tied. The drums were punctured or otherwise damaged and, for the most part, were empty, but three or four contained some dark oily liquid. Close examination of these drums revealed lettering still visible on one which read *Cashew Shell Liquid!*
>
> The cause of the epidemic had been found.
>
> At the shipyard, management quickly announced the facts over a public address system to the workmen so that their fears would be allayed. A strike was averted, and the ship was completed ahead of schedule. Further investigation revealed that cashew shell liquid had been spilled on the dock to some extent, in the street to a considerable amount, and extensively scattered over the sand lot in question. Many of the men working at refinishing and repairing this ship had sat on the sand, or the drums themselves, during the noon hour while they ate their lunches. Others had stretched out in the sun, bare-backed, on the contaminated sand. A check into the source of the drums revealed that a cargo of 1000 drums of the liquid had arrived and been unloaded on the opposite side of this same dock about one month previously. This work had been done by an outside contractor who had dumped the damaged drums onto the unused lot.
>
> At our suggestion, all suspicious-looking spots were covered with chlorinated lime, the dock was cleaned and scrubbed, the drums disposed of, and dirt filled in on the sand lot. The dermatitis, which by now was starting to appear in the homes of workmen, from contact with soiled clothing, quickly disappeared. My colleague, the shipyard's chemist, however, in a sincere effort to convince himself and others of the potency of the cashew liquid, became impatient at negative results obtained in 24 hours with one tiny patch test and tried four more generous patches with samples from different drums. A few days later he joined those who had been hospitalized.

This is not a medical book nor is it intended for legal reference. Its primary purpose is not to aid in the diagnosis and treatment of disease, the winning of compensation, or the refutation of false claims. If it should prove of use in such instances by making some facts more widely available, it may be presumed that the more light that can be thrown upon these phases of industrial medicine and industrial relations the better. It is hoped that much information of use in preventive medicine is included. Diagnostic signs of absorption or of early effects, in advance of injury, are eagerly sought by the progressive industrial physician, and, although time-proved and recognized tests are disappointingly few, the research-minded industrial physician will find opportunities for increasing this field of knowledge. The object of this book is to present industrial hygiene and toxicology in simple, understandable terms in sufficient detail to be of some use to all persons interested in safeguarding the health and welfare of working people and in improving the working environment. Essential requisites for the completely successful advancement of the health and safety of the breadwinning population include: (*1*) competent persons in health and safety maintenance departments; (*2*) managerial interest and appreciation of the benefits to be derived from health and safety work; and (*3*) teamwork—camaraderie, and cooperative efforts among industrial hygiene, medical, and safety personnel.

The welfare of an individual workman involves not only a working environment that gives reasonable assurance of freedom from accidental injury or occupational disease, but also his mental, temperamental, and physical fitness for the work to be done. Incentive, whether in the form of tangible assets to supply the necessities and some of the pleasures of life, or some expression of interest or recognition of accomplishments, ability, and efforts may be involved indirectly, but are somewhat outside the field of industrial hygiene.

It is not possible to maintain a uniform style in a collaboration, but the collective viewpoints compensate for some variations in style. The book is liberally supplied with references for the benefit of those whose wish to pursue the subjects in greater detail.

Frank A. Patty

Detroit, Michigan
October, 1948

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USEFUL EQUIVALENTS AND CONVERSION FACTORS

1 kilometer = 0.6214 mile
1 meter = 3.281 feet
1 centimeter = 0.3937 inch
1 micron = 1/25,400 inch = 40 microinches = 10,000 Angstrom units
1 foot = 30.48 centimeters
1 inch = 25.40 millimeters
1 square kilometer = 0.3861 square mile (U.S.)
1 square foot = 0.0929 square meter
1 square inch = 6.452 square centimeters
1 square mile (U.S.) = 2,589,998 square meters = 640 acres
1 acre = 43,560 square feet = 4,047 square meters
1 cubic meter = 35.315 cubic feet
1 cubic centimeter = 0.0610 cubic inch
1 cubic foot = 28.32 liters = 0.0283 cubic meter = 7.481 gallons (U.S.)
1 cubic inch = 16.39 cubic centimeters
1 U. S. gallon = 3.7853 liters = 231 cubic inches = 0.13368 cubic foot
1 liter = 0.9081 quart (dry), 1.057 quarts (U.S., liquid)
1 cubic foot of water = 62.43 pounds (4°C.)
1 U.S. gallon of water = 8.345 pounds (4°C.)
1 kilogram = 2.205 pounds
1 gram = 15.43 grains
1 pound = 453.59 grams
1 ounce (avoir.) = 28.35 grams
1 gram mole of a perfect gas ≎ 24.45 liters (at 25°C. and 760 mm. Hg barometric pressure)
1 atmosphere = 14.7 pounds per square inch
1 foot of water pressure = 0.4335 pound per square inch
1 inch of mercury pressure = 0.4912 pound per square inch
1 dyne per square centimeter = 0.0021 pound per square foot
1 gram calorie = 0.00397 B.t.u.
1 B.t.u. = 778 foot-pounds
1 B.t.u. per minute = 12.96 foot-pounds per second
1 hp. = 0.707 B.t.u. per second = 550 foot-pounds per second
1 centimeter per second = 1.97 feet per minute = 0.0224 mile per hour
1 foot candle = 1 lumen incident per square foot = 10.764 lumens incident per square meter
1 grain per cubic foot = 2.29 grams per cubic meter
1 milligram per cubic meter = 0.000437 grains per cubic foot

To convert degrees centigrade to degrees Fahrenheit: °C. (9/5) + 32 = °F.

To convert degrees Fahrenheit to degrees centigrade: (5/9) (°F. − 32) = °C.

For solutes in water: 1 mg./liter ≎ 1 p.p.m. (by weight)

Atmospheric contamination: 1 mg./liter ≎ 1 oz./1000 cu. ft. (approx.)

For gases or vapors in air at 25°C. and 760 mm. Hg. pressure:

To convert mg./liter to p.p.m. (by volume): mg./liter (24,450/mol. wt.) = p.p.m.

To convert p.p.m. to mg./liter: p.p.m. (mol. wt./24,450) = mg./liter

CONVERSION TABLE FOR GASES AND VAPORS[a]

(Milligrams per Liter to Parts per Million and Vice Versa; 25° C. and 760 mm. Mercury Barometric Pressure)

Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.
1	24,450	0.0000409	51	479	0.002086	101	242.1	0.00413
2	12,230	.0000818	52	470	.002127	102	239.7	.00417
3	8,150	.0001227	53	461	.002168	103	237.4	.00421
4	6,113	.0001636	54	453	.002209	104	235.1	.00425
5	4,890	.0002045	55	445	.002250	105	232.9	.00429
6	4,075	.0002454	56	437	.002290	106	230.7	.00434
7	3,493	.0002863	57	429	.002331	107	228.5	.00438
8	3,056	.000327	58	422	.002372	108	226.4	.00442
9	2,717	.000368	59	414	.002413	109	224.3	.00446
10	2,445	.000409	60	408	.002554	110	222.3	.00450
11	2,223	.000450	61	401	.002495	111	220.3	.00454
12	2,038	.000491	62	394	.00254	112	218.3	.00458
13	1,881	.000532	63	388	.00258	113	216.4	.00462
14	1,746	.000573	64	382	.00262	114	214.5	.00466
15	1,630	.000614	65	376	.00266	115	212.6	.00470
16	1,528	.000654	66	370	.00270	116	210.8	.00474
17	1,438	.000695	67	365	.00274	117	209.0	.00479
18	1,358	.000736	68	360	.00278	118	207.2	.00483
19	1,287	.000777	69	354	.00282	119	205.5	.00487
20	1,223	.000818	70	349	.00286	120	203.8	.00491
21	1,164	.000859	71	344	.00290	121	202.1	.00495
22	1,111	.000900	72	340	.00294	122	200.4	.00499
23	1,063	.000941	73	335	.00299	123	198.8	.00503
24	1,019	.000982	74	330	.00303	124	197.2	.00507
25	978	.001022	75	326	.00307	125	195.6	.00511
26	940	.001063	76	322	.00311	126	194.0	.00515
27	906	.001104	77	318	.00315	127	192.5	.00519
28	873	.001145	78	313	.00319	128	191.0	.00524
29	843	.001186	79	309	.00323	129	189.5	.00528
30	815	.001227	80	306	.00327	130	188.1	.00532
31	789	.001268	81	302	.00331	131	186.6	.00536
32	764	.001309	82	298	.00335	132	185.2	.00540
33	741	.001350	83	295	.00339	133	183.8	.00544
34	719	.001391	84	291	.00344	134	182.5	.00548
35	699	.001432	85	288	.00348	135	181.1	.00552
36	679	.001472	86	284	.00352	136	179.8	.00556
37	661	.001513	87	281	.00356	137	178.5	.00560
38	643	.001554	88	278	.00360	138	177.2	.00564
39	627	.001595	89	275	.00364	139	175.9	.00569
40	611	.001636	90	272	.00368	140	174.6	.00573
41	596	.001677	91	269	.00372	141	173.4	.00577
42	582	.001718	92	266	.00376	142	172.2	.00581
43	569	.001759	93	263	.00380	143	171.0	.00585
44	556	.001800	94	260	.00384	144	169.8	.00589
45	543	.001840	95	257	.00389	145	168.6	.00593
46	532	.001881	96	255	.00393	146	167.5	.00597
47	520	.001922	97	252	.00397	147	166.3	.00601
48	509	.001963	98	249.5	.00401	148	165.2	.00605
49	499	.002004	99	247.0	.00405	149	164.1	.00609
50	489	.002045	100	244.5	.00409	150	163.0	.00613

Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.	Molecular Weight	1 mg./l. p.p.m.	1 p.p.m. mg./l.
151	161.9	0.00618	201	121.6	0.00822	251	97.4	0.01027
152	160.9	.00622	202	121.0	.00826	252	97.0	.01031
153	159.8	.00626	203	120.4	.00830	253	96.6	.01035
154	158.8	.00630	204	119.9	.00834	254	96.3	.01039
155	157.7	.00634	205	119.3	.00838	255	95.9	.01043
156	156.7	.00638	206	118.7	.00843	256	95.5	.01047
157	155.7	.00642	207	118.1	.00847	257	95.1	.01051
158	154.7	.00646	208	117.5	.00851	258	94.8	.01055
159	153.7	.00650	209	117.0	.00855	259	94.4	.01059
160	152.8	.00654	210	116.4	.00859	260	94.0	.01063
161	151.9	.00658	211	115.9	.00863	261	93.7	.01067
162	150.9	.00663	212	115.3	.00867	262	93.3	.01072
163	150.0	.00667	213	114.8	.00871	263	93.0	.01076
164	149.1	.00671	214	114.3	.00875	264	92.6	.01080
165	148.2	.00675	215	113.7	.00879	265	92.3	.01084
166	147.3	.00679	216	113.2	.00883	266	91.9	.01088
167	146.4	.00683	217	112.7	.00888	267	91.6	.01092
168	145.5	.00687	218	112.2	.00892	268	91.2	.01096
169	144.7	.00691	219	111.6	.00896	269	90.9	.01100
170	143.8	.00695	220	111.1	.00900	270	90.6	.01104
171	143.0	.00699	221	110.6	.00904	271	90.2	.01108
172	142.2	.00703	222	110.1	.00908	272	89.9	.01112
173	141.3	.00708	223	109.6	.00912	273	89.6	.01117
174	140.5	.00712	224	109.2	.00916	274	89.2	.01121
175	139.7	.00716	225	108.7	.00920	275	88.9	.01125
176	138.9	.00720	226	108.2	.00924	276	88.6	.01129
177	138.1	.00724	227	107.7	.00928	277	88.3	.01133
178	137.4	.00728	228	107.2	.00933	278	87.9	.01137
179	136.6	.00732	229	106.8	.00937	279	87.6	.01141
180	135.8	.00736	230	106.3	.00941	280	87.3	.01145
181	135.1	.00740	231	105.8	.00945	281	87.0	.01149
182	134.3	.00744	232	105.4	.00949	282	86.7	.01153
183	133.6	.00748	233	104.9	.00953	283	86.4	.01157
184	132.9	.00753	234	104.5	.00957	284	86.1	.01162
185	132.2	.00757	235	104.0	.00961	285	85.8	.01166
186	131.5	.00761	236	103.6	.00965	286	85.5	.01170
187	130.7	.00765	237	103.2	.00969	287	85.2	.01174
188	130.1	.00769	238	102.7	.00973	288	84.9	.01178
189	129.4	.00773	239	102.3	.00978	289	84.6	.01182
190	128.7	.00777	240	101.9	.00982	290	84.3	.01186
191	128.0	.00781	241	101.5	.00986	291	84.0	.01190
192	127.3	.00785	242	101.0	.00990	292	83.7	.01194
193	126.7	.00789	243	100.6	.00994	293	83.4	.01198
194	126.0	.00793	244	100.2	.00998	294	83.2	.01202
195	125.4	.00798	245	99.8	.01002	295	82.9	.01207
196	124.7	.00802	246	99.4	.01006	296	82.6	.01211
197	124.1	.00806	247	99.0	.01010	297	82.3	.01215
198	123.5	.00810	248	98.6	.01014	298	82.0	.01219
199	122.9	.00814	249	98.2	.01018	299	81.8	.01223
200	122.3	.00818	250	97.8	.01022	300	81.5	.01227

[a] A. C. Fieldner, S. H. Katz, and S. P. Kinney, "Gas Masks for Gases Met in Fighting Fires," *U. S. Bur. Mines, Tech. Paper* No. **248** (1921).

CONTENTS

Volume I

I. Industrial Hygiene—Retrospect and Prospect. By FRANK A. PATTY........ 1
- I. Historical Résumé........ 1
  - A. Medical and Industrial Hygiene Literature........ 1
  - B. Labor Legislation........ 4
  - C. Significant Events in the Progress of Industrial Hygiene in the United States........ 5
- II. World War II and Industrial Hygiene Service........ 9
  - A. Official Agencies........ 9
  - B. Insurance and Industrial Groups........ 9
  - C. Educational Institutions........ 10
  - D. Research Organizations........ 11
- III. Industrial Hygiene in Foreign Countries........ 11
  - A. England........ 11
  - B. Russia........ 12
  - C. Germany........ 13
  - D. Other Countries........ 13
- IV. Industrial Hygiene in the United States........ 14
- V. Prospective Roles of Industrial Hygiene........ 14

II. Industrial Hygiene Records and Reports. By RUTH B. PATTY........ 19
- I. Introduction........ 19
- II. Types of Plant Records........ 20
  - A. Records of the Environment........ 21
  - B. Medical Examination Records........ 21
  - C. Nurse's Records........ 22
  - D. Records of Biological Specimens........ 23
  - E. Safety Records........ 26
  - F. Personnel Records........ 26
  - G. Compensation Claim Records........ 26
- III. Collection of Data about the Environment........ 30
- IV. Statistical Analysis of Data........ 32
  - A. First Inspection........ 32
  - B. Averages........ 32
  - C. Dispersion........ 34
  - D. Correlation........ 35
  - E. Presentation of Data........ 35
- V. Industrial Hygiene Reports........ 37
- VI. Research........ 38
- VII. Conclusion........ 39

III. The Industrial Hygiene Survey and Personnel. By FRANK A. PATTY........ 41
- I. Introduction........ 41

42
- II. Types of Surveys 42
  - A. The Inspection Survey 42
  - B. The Preliminary Industrial Hygiene Survey 43
  - C. The Investigational Industrial Hygiene Survey 44
  - D. The Combined Industrial Hygiene and Medical Survey 52
- III. The Industrial Hygiene Unit 52
- IV. Qualifications and Training of Personnel 54
  - A. Administrative Industrial Hygienist 54
  - B. Industrial Hygienist 54
  - C. Other Personnel 55

IV. Human Engineering and Industrial Safety. By Ross A. McFarland 57
- I. Introduction 57
  - A. The Role of Human Engineering in Accident Prevention 57
  - B. Principles of Advance Analysis 59
- II. Equipment Design in Relation to Human Body Size 63
  - A. The Application of Anthropometric Data 64
- III. Equipment Design in Relation to Human Capabilities 83
  - A. Visual Displays 83
  - B. Other Sensory Displays 92
  - C. Controls 93
- IV. Design of the Working Area in Relation to Environmental Variables 108
  - A. Temperature and Humidity 110
  - B. Noise and Vibration 111
- V. Summary and Conclusions 115

V. Industrial Sanitation. By M. A. Shapiro 117
- I. Provision of a Safe, Potable, and Adequate Water Supply 117
  - A. Source and Regulatory Control of the Water Supply 117
  - B. Drinking and Culinary Water 118
  - C. Water Uses in Industry 119
  - D. Conservation of Water in Industry 120
  - E. Cross Connections 121
  - F. Elimination of Cross Connections 122
  - G. Cross Connection Surveys 124
- II. Collection and Disposal of Liquid and Solid Wastes 125
  - A. Sewage and Other Liquid Wastes 126
  - B. Solid Wastes 127
- III. Assurance of a Safe Food Supply 128
  - A. Illnesses Due to Ingestion of Food 128
  - B. Food Handling 131
  - C. Kitchen and Kitchen Equipment Design 132
  - D. Food Vending Machines 133
- IV. Control and Elimination of Insects and Rodents 134
  - A. Insect Control 134
  - B. Rodent Control 135
  - C. Ratproofing (Building Out the Rat) 135
  - D. Killing Rats 136
- V. Provision of Adequate Sanitary Facilities and Other Personal Services 136
- VI. Maintenance of General Cleanliness of the Industrial Establishment 140
- VII. The Sanitary Engineer in Industry 140

VI. The Mode of Entry and Action of Toxic Materials. By Frank A. Patty... 143
I. Classification of Contaminants... 143
  A. Physical Classifications... 144
  B. Chemical Classifications... 144
  C. Physiological Classifications... 144
II. Respiration... 146
  A. Mechanics of Respiration... 146
  B. Lung Structure, Vital Capacity, and the Dead Space... 147
  C. Regulation and Control of Respiration... 148
  D. Function of Hemoglobin... 149
  E. Circulation as a Factor, and Its Regulation... 149
III. Absorption, Distribution, and Elimination... 150
  A. Modes of Expressing Concentrations... 150
  B. Volume-Pressure-Temperature Relations... 152
  C. Role of Solubility in Absorption of Gases and Vapors... 153
  D. Dusts and Fumes... 160
  E. Mists... 161
  F. Other Means of Absorption... 162
IV. Standards of Physiological Response... 162
V. Standards for Permissible Atmospheric Contamination and How They Are Set 164

VII. Sampling and Analysis of Atmospheric Contaminants. By Frank A. Patty 173

Gases and Vapors

I. Methods Giving Quantitative Results in the Field... 174
  A. Evaluating the Intensity of Odor and Irritation... 174
  B. Portable Rapidly Indicating Devices... 178
  C. Collection in Indicator Medium... 183
  D. Hand Piston Pump, Luer Syringe, and Rubber-Bulb Collection Devices... 184
II. Methods Requiring Laboratory Analysis... 185
  A. Halogenated Hydrocarbons Combustion Apparatus... 185
  B. Adsorption for Evaluation by Weight... 187
  C. Condensation at Low Temperatures... 188
  D. Collection by Absorption or Adsorption for Laboratory Analysis... 188
  E. Sampling in Evacuated Bottles... 188
  F. Spectrometry... 189
  G. Thermal Conductivity... 190

Dust, Fumes, and Smokes

I. Sampling... 190
  A. Impingement... 190
  B. Electrostatic Precipitation... 193
  C. Filtration... 194
  D. Thermal Precipitation... 195
  E. Sedimentation... 195
II. Evaluation of Dust Samples... 195
  A. Making a Dust Count... 196
  B. Determining Particle Size Distribution... 201
  C. Weighing the Sample... 204
  D. Analyzing the Dust... 204

Bacteria and Other Microorganisms ... 209

Physical Characteristics of the Environment ... 210

VIII. Air Conditioning. By Kenneth E. Robinson 211
- I. Physical and Physiological Principles 211
  - A. Effective Temperature Scale and Comfort Zone 214
- II. Environmental Control 218
  - A. Adding Heat to a Space 218
  - B. Removing Heat from a Space 221
  - C. Humidification 224
  - D. Dehumidification 224
  - E. Air Distribution 225

IX. Air Cleaning. By W. N. Witheridge 229
- I. Applications of Air Cleaning 229
  - A. Air-Conditioning Applications 229
  - B. Air-Pollution Control Applications 230
- II. Air Quality Requirements 230
  - A. Permissible Concentrations for Indoor Discharge 231
  - B. Weight, Count, and Visual Ratings 231
  - C. Black-White Distinction for Air-borne Matter 231
  - D. Removal of Air-borne Organisms 232
- III. Properties of Aerodispersions 232
  - A. Properties of the Carrier Gas 232
  - B. Properties of Air Contaminants 233
- IV. Specification of Performance 237
  - A. Efficiency or Effectiveness 237
  - B. Separation Degree 238
  - C. Referent Difficulty of Separation 239
- V. Classification of Cleaning Processes 240
- VI. Preparation of Aerodispersions 242
- VII. Gravitational Separators 242
- VIII. Inertial Separators 244
  - A. Baffle or Impact Separators 246
  - B. Louvered or Slotted Separators 246
  - C. Cyclone Separators 247
  - D. Rotary Centrifugal Separators 247
- IX. Filters 247
  - A. Impingement Filters 251
  - B. Viscous Filter Media 252
  - C. Paper Filters 252
  - D. Cloth Filters 253
  - E. Absolute Filters 255
  - F. Gas or Vapor Adsorption Filters 255
- X. Electric Precipitators 255
  - A. Single-Stage High-Voltage Precipitators 257
  - B. Two-Stage Low-Voltage Precipitator 260
- XI. Washers or Scrubbers 262
  - A. Spray Chambers or Towers 268
  - B. Deflection Orifice Scrubbers 268
  - C. Packed Towers 268
- XII. Comparison of Dry and Wet Systems of Air Cleaning 270
- XIII. Combination Systems of Treatment 272
  - A. Sequence of Separating Stages 272
  - B. Two-Stage Cleaning Systems 274

C. Concentrators: Subdivision of Air Streams 274
XVI. Entrainment Prevention 274
A. Air Turbulence 274
B. Viscous Liquids or Adhesives 275
XV. Continuous Service Arrangements 275
A. Temporary Removal from Service 276
B. Conveyorized or Recirculating Separator Elements 276
C. Reverse-Air Cleaning of Filter Fabrics 276
XVI. Waste Disposal 277
XVII. Selection for Specific Requirements 278
A. Versatility 278
B. Incompatibilities of Aerodispersion and Equipment 278
C. Incompatibility of Liquid Agitation and Sedimentation 279
D. Fire or Explosion Hazards 279
E. Cost Analysis 280
F. Power Requirements 281

X. Ventilation. By W. N. WITHERIDGE 285
I. Human Ventilation Requirements 286
A. Air Composition 286
B. Carbon Dioxide as an Index of Ventilation Requirements 287
C. Effect of Room Size on Ventilation Requirements 288
D. Mines, Tunnels, and Underground Spaces 289
II. General Ventilation 289
A. Classification of General Ventilation 290
B. General Ventilation Specifications 291
C. Dispersion of Air Contaminants by General Ventilation 296
D. Air-Supply Inlets and Exhaust Outlets 296
E. Short-circuiting the Air Supply 298
F. Progressive Ventilation 298
G. General Ventilation vs. Local Exhaust Ventilation 299
III. Industrial Process Ventilation 299
A. Industrial Process Enclosures 299
B. Local Exhaust Ventilation 303
C. Central vs. Unit Exhaust Systems 319
IV. Aeromotive Methods and Equipment 322
A. Natural Aeromotive Forces 322
B. Mechanical Aeromotive Forces 326
V. Design of Ducts for Exhaust Systems 329
A. Procedure for Design of Exhaust Systems 329
B. Design Example 332
C. Relation between Air Velocity and Velocity Pressure 337
D. Air-Duct Friction 337
E. Reynolds Number 338
F. Flexible Metal, Canvas, or Rubber Ducts 339
G. Adjustable Dampers or Flow Regulators 339
H. Pneumatic Conveying Systems 340
I. Construction Specifications for Ventilating Systems 340
J. Maintenance of Ventilating Equipment 340

XI. Respirators and Respiratory Protective Devices. By FRANK A. PATTY 343
I. Historical Résumé and Present Approval Procedure 343

II. Types and Uses of Respiratory Protective Devices 344
A. Air-Purifying Respirators 344
B. Atmosphere-Supplying Respirators 348
C. Unapproved Equipment 350
III. Selection of a Respirator 352
IV. Cleaning and Sterilizing 354
V. Examining a Respirator 354

XII. The Pulmonary Dust Diseases. By O. A. Sander, M.D. 357
I. Introduction 357
A. Properties of Dust 358
B. Atmospheric Dust Concentrations and Particle Size 359
II. Classification of Dust Based on Its Effect in the Body 360
III. Anatomical Factors of Importance in Injury by Dust 362
IV. Physiological Factors of Importance in Injury by Dust 367
V. Dust Causing Pulmonary Fibrosis 367
A. Silicosis 367
B. Asbestosis 397
C. Bauxite Pneumoconiosis (Shaver's Disease) 400
D. Diatomaceous Earth Pneumoconiosis (Diatomite Silicosis; Diatomite Pneumoconiosis) 401
E. Coal Workers' Pneumoconiosis (Anthracosilicosis; Anthracosis) 404

XIII. Air Pollution. By George D. Clayton 413
I. History 413
II. Effects of Air Pollution 414
A. Acute Effects on People 414
B. Chronic Effects on People 418
C. Effects on Vegetation 420
D. Effects on Structures 422
III. Economics of Air Pollution 423
IV. Sources and Kinds of Air Pollution 424
A. Pollution in Various Cities 425
V. Control Procedures 429
A. Air-Cleaning Devices 433
B. Dilution 433
C. Substitution 434
D. Zoning 435
VI. Legislation 435
A. Past Precedents 435
B. Present Status 437
VII. Meteorology and Topography 438
A. Importance in Plant Location 438
B. Effect on Air Pollutants 439
VIII. Practical Considerations for Plant Management 440

XIV. Occupational Dermatoses. By Louis Schwartz, M.D. 443
I. Historical Data 443
II. Incidence 444
III. Causes of Occupational Dermatoses and Their Classification 445
A. Predisposing Causes 445
B. Actual Causes 448
IV. Clinical Types of Occupational Dermatitis 454

V. Diagnosis of Occupational Dermatoses 455
  A. The Patch Test in Industry 457
VI. Prevention of Occupational Dermatoses 461
  A. Pre-employment Examinations 461
  B. Ventilation 462
  C. Protective Clothing 462
  D. Cleanliness 464
  E. Protective Ointments 465
VII. Treatment 467
VIII. Occupational Cancer 468
  A. Sources of Occupational Cancer 468
  B. Prevention of Occupational Cancer 469
IX. Methods of Investigation 469
X. Skin Hazards According to Types of Workers or Occupations 471

XV. **The Visible Marks of Occupation and Occupational Diseases.** By CAREY P. McCORD, M.D 479
  I. Introduction 479
  II. Stigmata of Degeneration 481
  III. Marks from Work and Work Diseases 484
  IV. Summary 484
  V. Common External Marks of Occupation or Occupational Diseases or Other Diseases (Table) 486

VI.—**Section One. Fire and Explosion Hazards of Combustible Gases and Vapors.** By G. W. JONES 511
  I. Limits of Flammability 511
    A. Factors Affecting the Limits of Flammability 512
    B. Limits of Flammability of Gases and Vapors in Air 513
    C. Calculation of Limits of Flammability 514
    D. Limits of Flammability of Gases and Vapors in Oxygen 523
  II. Ignition Temperatures 524
    A. Factors Affecting Ignition Temperature 524
    B. Minimum Ignition Temperatures of Gases and Vapors 525
    C. Ignition Temperatures in Air and Oxygen 532
  III. Flash Points 532
  IV. Temperature Range of Flammability 535
  V. Methods of Minimizing Explosions 538
    A. Control of the Oxygen Content of the Atmosphere 538
    B. Operating Outside the Range of Flammability 542
    C. Use of Less Flammable Materials 542
    D. Elimination of Ignition Sources 544
    E. Segregation of Hazardous Operations 545
    F. Provision of Adequate Ventilation 545
    G. Release Diaphragms and Vents 546
    H. Combustible Gas Indicators for Flammable Atmospheres 548

XVI.—**Section Two. Explosion and Fire Hazards of Combustible Dusts.** By IRVING HARTMANN 549
  I. The Explosion Hazard 549
    A. Factors Affecting Explosibility of Dusts 550
  II. Laboratory Data on Dust Explosibility 558
    A. Data on Ignition Temperatures 559

B. Minimum Explosive Concentrations 562
C. Minimum Energy Required for Ignition 564
D. Maximum Pressure and Rates of Pressure Rise in Dust Explosions 566
E. Relative Flammability of Dusts 569
III. The Fire Hazard 569
A. Prevention of Dust Explosions and Fires 571

XVII. Physiological Effects of Abnormal Atmospheric Pressure. By Heinz Specht 579
I. Introduction—Historical Background 579
II. Properties of the Atmosphere 581
A. Composition 581
B. Physical Attributes of Atmospheric Gases and Fundamental Physiological Aspects 582
C. Chemical Activity 591
III. Effects of Increased Atmospheric Pressure on the Body 594
A. Charging of the Body with Gases 594
B. Effects of Maintained Positive Atmospheric Pressure 597
C. Discharge of Gases from the Body Following Exposure to Increased Atmospheric Pressure: Decompression 601
IV. Effects of Reduced Atmospheric Pressure on the Body 606
A. Discharge of Gases from the Body: Decompression 607
B. The Effects of Maintained Low Atmospheric Pressure 611
C. Charging of the Body with Gas in Descent: Recompression 617
V. Comparison of Effects of High and Low Atmospheric Pressure 619

XVIII. Industrial Noise and the Conservation of Hearing. By Jerome R. Cox, Jr. 621
I. Fundamentals of Noise 622
A. What is Sound? 622
B. Pure Tones 622
C. Frequency 623
D. Wave Length 623
E. Sound Pressure 623
F. Sound Power 624
G. Sound Intensity 624
H. The R.M.S. Sound Pressure 627
I. Complex Sounds 627
J. Frequency Analysis 628
K. Frequency Bands 630
L. The Decibel 632
M. Intensity Level 634
N. Sound Pressure Level 636
O. Some Common Sounds 637
II. The Transmission of Sound 637
A. Radiation from a Simple Sound Source 639
B. The Inverse-Square Law 639
C. Sound in a Room with Nonabsorbing Walls 640
D. The Absorption of Sound 641
E. The Absorption Coefficient 641
F. Sound in a Room with Absorbing Walls 643
G. The Transmission of Sound through Partitions 645
H. The Mass Law 648
I. Transmission of Sound through Composite Structures 650

J. Transmission of Sound from One Room to Another 651
K. A Practical Example 653
III. The Ear and the Measurement of Hearing 656
A. The Ear 656
B. The Measurement of Hearing 657
C. Threshold of Hearing 659
D. Normal Hearing 660
E. Pure-Tone Audiometry 660
F. Sound Intensity Produced by the Earphones 662
G. Physical Methods of Calibration 663
H. Psychophysical Methods of Calibration 664
I. Masking 664
J. How Quiet Must It Be to Measure Normal Hearing? 665
K. General Principles of Audiometer Room Design 665
L. Speech Audiometry 666
M. Relation between the Thresholds for Pure Tones and Speech 668
N. Audiometric Programs 668
O. Hearing Impairment 669
P. Characteristics of Hearing Loss Resulting from Noise 670
Q. Relations of Hearing Impairment to Noise Exposure 671
R. The Severity of a Noise Exposure 672
S. How Much Noise Exposure Causes Hearing Disability? 673
T. Engineering Criteria for Noise Control 674
U. The Relation of Noise Exposure to Sound Energy 675
IV. Noise Control 675
A. Control of Noise at the Source 676
B. Control of Noise by Enclosure 685
C. Control of Noise by Sound-Absorbing Materials 688
D. Control of Noise by Ear Protection 689

XIX. Radiant Energy. By Leon F. Curtiss 695
I. Fundamental Concepts of the Production of Injury by Radiation 695
A. Ionization as a Cause of Injury 695
B. Target Theory 695
C. Injuries in Higher Forms of Life 696
D. Genetic Effects of Radiation 696
E. Visible Evidence of Injurv from Radiation 700
II. Penetrating Ionizing Radiation 701
A. Types of Exposures and Injuries 701
B. Latent Period 702
C. Tolerance Dose 702
D. Health Physicist 704
E. Blood Counts as Index of Injury 706
F. Radioisotopes 706
G. Protection from Gamma Rays 709
H. Protection from X-rays 714
III. Infrared Radiation 719
A. General Effect 719
B. Protective Measures 719
IV. Corpuscular Radiation 720
A. Beta Rays 720
B. Neutrons 720

V. Poisoning from Radioisotopes 722
  A. Radium Poisoning 722
  B. Thorium Poisoning 739
  Handbooks of the National Bureau of Standards on Radiation Protection 742

XX. Lighting for Seeing. By SYLVESTER K. GUTH and E. A. LINSDAY 743
I. Lighting Terms and Units 744
II. Visibility 745
III. Ease of Seeing 751
IV. Quality of Lighting 752
V. Color 755
VI. The Human Element 755
VII. Light Sources 759
  A. Filament Lamps 759
  B. Mercury Lamps 759
  C. Fluorescent Lamps 760
  D. Germicidal Lamps 760
  E. Infrared Lamps 761
VIII. Lighting Benefits 761
IX. General Lighting 774
  A. Maintenance 778
X. Supplementary Lighting 780
XI. Infrared Radiation 787
XII. Ultraviolet Radiation 787

XXI. Heat Control in the Hot Industries. By T. F. HATCH 789
I. Effects of Heat on Man 790
II. Physiological Limits of Heat Exposure 791
  A. Haldane's Wet-Bulb Temperature Limits 791
  B. Exposure Limits in Terms of Effective Temperature 792
  C. Physiological Limits Based on Performance Ability 792
  D. Maximum Permissible Sweat Rate 793
  E. Calculated Limits of Heat Exposure to Maintain Thermal Balance 794
  F. Physical Basis of Tolerance Lines 795
  G. Limits of Heat Exposure Fixed by Thermal Balance and Maximum Permissible Sweat Rate 798
III. Physical Evaluation of Hot Environments 799
IV. Heat Control 801
  A. Control at Source 801
  B. General Building Ventilation 804
  C. Localized Ventilation and Cooling at Fixed Work Stations 804
V. Supervision of Employees in Hot Industries 805
  A. Safe Tolerance Limits and Intermittent Rest Periods 806
  B. Medical Supervision 807

Index 809

CHAPTER I

Industrial Hygiene—Retrospect and Prospect

FRANK A. PATTY

Historical accounts down through the ages are replete with allusions to the unattractive lot of the man who has earned his livelihood by manual labor. In ancient times a considerable portion of such work was done by slaves, a practice that has been extended in instances even into the twentieth century. Where slave labor has been employed there has not been sufficient incentive or opportunity to study the adverse effects of occupational environments.

Early beliefs that unhealthful conditions are inherent in certain trades have now been disproved and are no longer generally expressed; when plant operators today are presented with clear-cut evidence of unhealthful working environments they are almost universally ready to institute any practical control measures. One of the industries that rather recently joined the modern trend toward providing clean as well as healthful environments was the foundry industry, and even today some foundry operators still believe that considerable dirt, dust, and fumes are inherent in the industry. This is not an expression of conservatism among foundry management, but rather the result of the failure of the layout man, the industrial hygienist, and the ventilation engineer to provide information on the correct design of foundries and foundry equipment as well as on correct ventilation practices. No one wants a dirty work place if it is easy, practical, and economically feasible to have a clean one. Neither does management want to spend huge sums for dust control only to find that it does not do what it was intended to do. Although there may still be isolated employers who regard labor as a commodity purchasable on the market and more easily replaced than preserved, the vast majority of workmen in the United States today are in a very enviable position with respect to the safeguards taken to protect them from occupational diseases and accidents.

I. Historical Résumé

A. MEDICAL AND INDUSTRIAL HYGIENE LITERATURE

Lead poisoning is the oldest recorded occupational disease. Hippocrates, who lived in the fourth century B.C. and is credited with lifting the practice of medicine from its basis of superstition and giving it a scientific foundation, has also been credited by some with being the first to record adverse effects upon miners and metallurgists from exposure to lead.

Pliny the Elder, in the first century A.D., in his encyclopedia of natural science, refers to the use of bladders that "minium refiners" wore over their faces in an effort to avoid inhaling dust. "Minium" is the Latin word for cinnabar (red mercuric sulfide).

Medical history includes other brief references to occupational exposures, by such ancient authorities as Galen, Celsus, and others. However, it was not until the fifteenth century that further significant progress was recorded. In 1473 Ellenbog recognized that the vapors of some metals were dangerous, described the symptoms of industrial poisoning from lead and mercury, and suggested preventive measures. Agricola, a physician and mineralogist, in his *De re metallica* (1556) recognized "asthma" and ulceration of the lungs caused by the inhalation of certain kinds of dust. He stated that among the miners in the Carpathian Mountains some women married as many as seven husbands, each of whom succumbed to this disease.

Philippus Paracelsus (1493–1541), a Swiss chemist, physician, and professor of physics and surgery, with no academic degree, who was thoroughly disliked by the physicians of his time, was credited with being an independent thinker and investigator. He worked in Tyrol as a mining and smelting laborer for ten years, and then several years later returned to the mines to get material for his treatise on occupational diseases, in which he described various "miners' diseases," disturbances of the lungs, stomach, and intestines, that resulted from digging, smelting, and washing gold, silver, salt, alum, sulfur, lead, copper, zinc, iron, and mercury. He described chronic lung trouble of miners as "lung consumption, asthma, and dyspnea." He attributed the cause to vapors and emanations from the metals and advised that contact with them be avoided, as the condition was incurable.

Paracelsus pointed out fallacies of many medical theories then current, opposed the humoral theory of disease, and taught the use of specific remedies instead of indiscriminate bleeding and purging. Even though he introduced many new medicines, which are still in use today, he was regarded as a charlatan by physicians of his time—and still is in some circles. He died at the age of forty-eight. His untimely death has been variously attributed to "drunken debauchery," to his being thrown down a steep incline by assailants hired by his enemies, and to his contracting one of the occupational diseases he had described—perhaps the most plausible cause. His book was not published until 1567, twenty-six years after his death.

Ramazzini, in 1700, published the first book that could be considered a complete treatise on occupational diseases, *De morbis artificum diatriba*. A second and expanded edition appeared (in 1717) in which he discussed not only diseases resulting from exposure to dusts and metal fumes, but also those due to several chemicals. He accurately described, from personal observations, scores of occupations with their attendant hazards and emphasized the necessity for the physician to inquire into the occupation of the patient. So logical were many of his observations that they remain substantiated today. In the majority of instances, however, the measures he advocated for the control of occupational diseases were therapeutic and curative rather than preventive, a methodology that persists to a certain extent today, albeit in the more progressive circles the control of industrial health is preventive, through hygiene, sanitation, and periodic health examinations.

K. B. Lehmann, in his experiments on the toxic effects of gases upon animals, instituted a form of research about 1884 that has given us much of the information that serves as a guide for the control of industrial atmospheres today. A French pharmacist and chemist, Jean Baptiste Alphonse Chevallier (1793–1879), contributed liberally to the literature of industrial hygiene.

Many books on the medical and legal aspects of occupational diseases have been published in the last one hundred years, but few deal with industrial toxicology, and even fewer with the preventive engineering aspects of occupational disease control. A list of the more recent and better known books that include some of these subjects is given below:

Health of the Industrial Worker, E. L. Collis and Greenwood (1919).
Industrial Health, G. M. Kober and E. R. Hayhurst (1924).
Industrial Poisons in the United States, Alice Hamilton (1925).
Schädliche Gase, F. Flury and F. Zernik (1931).
Industrial Hygiene for Engineers and Managers, C. P. McCord and F. P. Allen (1931).
The Dermatergoses or Occupational Affections of the Skin, 4th ed., R. Prosser White (1934)
Occupation and Health, International Labor Office (1934).
Industrial Toxicology, Wm. N. McNally (1937).
Carbon Monoxide Asphyxia, C. K. Drinker (1938).
Toxicology and Hygiene of the Technical Solvents, K. B. Lehmann and F. Flury (1938).
Essentials of Industrial Health, C. O. Sappington (1943).
Industrial Medicine, F. J. Wampler (1943).
Manual of Industrial Hygiene, National Institutes of Health (1943).
Noxious Gases, Y. Henderson and H. W. Haggard (1943).
A Manual of Pharmacology, T. Sollman (1944).
Introduction to Industrial Medicine, T. Lyle Hazlett (1946).
The Industrial Environment and Its Control, J. M. DallaValle (1947).
Industrial Health Engineering, A. D. Brandt (1947).
Occupational Diseases of the Skin, 2nd ed., L. Schwartz, L. Tulipan, and S. M. Peck (1947).
Occupational Medicine and Industrial Hygiene, R. T. Johnstone (1948).
Analytical Chemistry of Industrial Poisons, Hazards, and Solvents, 2nd ed., M. B. Jacobs (1949).
Industrial Toxicology, L. T. Fairhall (1949).
Industrial Toxicology, 2nd ed., Alice Hamilton and H. L. Hardy (1949).
The Chemistry of Industrial Toxicology, H. B. Elkins (1950).
Handbook on Aerosols, Atomic Energy Commission (1950).
Handbook on Air Cleaning, S. K. Friedlander, L. Silverman, P. Drinker, and M. W. First (1952).
Noise, University of Michigan School of Public Health (1952).
Toxicity of Industrial Organic Solvents, rev. ed., E. Browning (1953).
General Handbook for Radiation Monitoring, Robert F. Barker (1954).
Industrial Dust, 2nd ed., P. Drinker and T. F. Hatch (1954).
Plant and Process Ventilation, W. C. L. Hemeon (1955).
Rosenau, *Preventive Medicine and Public Health,* 8th ed., K. F. Maxcy (1956).

B. LABOR LEGISLATION

Labor legislation has played an important part in the progress and development of industrial hygiene, both in the United States and abroad. It is said[1] that the deplorable state of orphaned child workers in English cotton mills was a major factor in motivating reforms in working conditions in factories, and that the initial step was taken by Sir Robert Peel, a millowner, by acquainting the English Parliament with these conditions in 1802. Other reformers became interested. Statistics gathered showed that the average age of the working classes was 22 as compared with an average age of 44 among the wealthier classes, and that the death rate in the workingmen's districts was appreciably higher than the general rate. The Factory Act was passed in 1833, limiting the hours of work of children and providing for factory inspection in certain factories and industries. Several trades were brought under the control of the Factory Act in 1864, and in 1867 the act was broadened to include many industries and those places employing more than 50 persons. This act prohibited the eating of meals in noxious plant atmospheres, provided for the guarding of machinery, and required mechanical ventilation for the control of injurious dusts. Medical inspection of factories was inaugurated in 1897, at which time the idea of compensation was adopted.

France and Germany also passed laws during the nineteenth century to regulate hours of labor and protect workmen in some of the more dangerous trades. Factory inspection was introduced in the United States by Massachusetts in 1877; soon thereafter Massachusetts, New Jersey, New York, Connecticut, Michigan, Missouri, and Minnesota passed laws requiring the removal of dusts and injurious gases by means of exhaust fans.

The United States became the last industrially important country to adopt compensation when in 1908 limited benefits were provided for United States Civil Service employees. New Jersey was the first state to pass such a law, in 1911. Other states followed rapidly in providing compensation for accidents. In 1911 California, Connecticut, Illinois, Michigan, New York, and Wisconsin passed laws requiring the reporting of, and later compensation for, cases of occupational disease. In 1919 Wisconsin made occupational diseases compensable and the majority of the states now have laws requiring such compensation. Some of these states recognize only a few specific diseases, whereas others recognize any disease of occupational origin, that is, a disease arising out of or in the course of and peculiar to the occupation. The general coverage law, while it is said by some to be conducive to fraudulent claims that are expensive to refute, is obviously the only completely fair coverage for the workman, whom it presumably is designed to protect. As an example of the obviously unfair situation that can result under the limited coverage statutes, one state, which has been a leader in making occupational diseases compensable, not long ago recognized diseases arising from exposure to "benzine

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[1] L. B. Chenoweth, W. Machle, and H. Schneider, *Industrial Hygiene*, Crofts, New York, 1938.

(petroleum products) and its homologues" but did not recognize diseases arising from exposure to benzene (benzol), nor silicosis arising from silica-bearing dusts. Both of these errors have since been corrected. Any fair-minded student of industrial hygiene appreciates the necessity of recognizing and controlling all exposures that adversely affect the health and well-being of employees, regardless of the nature of the exposure.

The first major public act that offered control of an occupational disease in the United States came in 1912 when the use of yellow phosphorus (also called white phosphorus) in the manufacture of matches was prevented by placing a prohibitive federal tax on its use for that purpose.

What was perhaps the first significant major investigation[2] of occupational disease in this country was undertaken by the United States Public Health Service and the United States Bureau of Mines jointly to determine the cause and extent of pulmonary diseases among lead and zinc miners.

C. SIGNIFICANT EVENTS IN THE PROGRESS OF INDUSTRIAL HYGIENE IN THE UNITED STATES

The first national conference on industrial diseases was called at Chicago in 1910 by the American Association for Labor Legislation, and a commission consisting of representatives of medicine, engineering, and chemistry was assigned the task of investigating the magnitude of the problem and of proposing a method of attack in a warfare against industrial disease. About this time several groups began the study of occupational diseases. The United States Bureau of Mines was created in 1910. The United States Bureau of Labor, set up in 1885, was made the Department of Labor in 1913. This department was charged with collecting "information upon the subject of labor, its relation to capital, the hours of labor, and the earnings of laboring men and women, and also upon the means of promoting their material, social, intellectual, and moral prosperity." The Department of Labor has been responsible for the collection and dissemination of much valuable information in the field of industrial hygiene. There have been attempts by this department either to wrest control of industrial hygiene activities from the United States Public Health Service or to set up a duplicate service. It seems evident that industrial hygiene is primarily a health problem, rather than a labor problem, notwithstanding the fact that a few states have successfully conducted their industrial hygiene activities under state departments of labor. A point upon which there is unanimous agreement is that there should not be an overlapping or duplication of effort by departments of health and labor.

The American Museum of Safety was created in New York in 1911 and later became known as Safety Institute of America, under which name it is still active along educational lines. The National Safety Council was organized in 1913. The American Public Health Association organized a section on Industrial Hygiene in

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[2] A. J. Lanza and E. Higgins, *U. S. Bur. Mines Tech. Paper* No. **105,** 1915.

1914. The United States Public Health Service organized a Division of Industrial Hygiene and Sanitation in 1915. The American Association of Industrial Physicians and Surgeons was organized in 1916. The ill health and increased mortality accompanying the accelerated production of munitions and other war materials for World War I made many persons conscious of the necessity for technical guidance in the recognition and control of occupational diseases. *The Journal of Industrial Hygiene* was established in 1919 and was the leading publication in the field. It was acquired by the American Medical Association in 1949, underwent editorial policy changes, and is presently (1957) published as the *A.M.A. Archives of Industrial Health.* The *American Industrial Hygiene Association Quarterly,* published for the first time in 1946, has had wide acceptance and is now the leading source of information in the industrial hygiene field. Starting January, 1958, it will be issued six times a year as the *American Industrial Hygiene Association Journal.*

In 1918 the Harvard Medical School established a Department of Applied Physiology, which in 1922 became a part of the present Harvard School of Public Health as the Department of Physiology and the Department of Industrial Hygiene. This was the first time that instruction and research in industrial hygiene leading to advanced degrees had been offered anywhere in the world. This school co-operates with the graduate school of engineering: any of the courses offered in the School of Public Health may be elected by students working for a degree of master or doctor of science in engineering. The School of Public Health, which is open to graduates of schools of medicine, and graduates in arts and sciences with training in basic medical sciences or specialized training and experience in an important phase of public health work, offers the degree of master of public health and, to especially qualified persons, the degree of doctor of public health. The Harvard School of Public Health was the first place in the world where a qualified person could obtain scheduled, broad instruction in industrial hygiene regardless of whether his undergraduate training had been in medicine or in the sciences. Several universities, colleges, and technological schools now provide similar instruction to a growing number of students.

Many chemists and engineers, as well as physicians, in the field have acquired their specialized industrial hygiene knowledge and skills by association and in the "School of Hard Knocks." Official agencies, such as the United States Bureau of Mines, United States Public Health Service, several state divisions of industrial hygiene, and a few city health department bureaus of industrial hygiene, have furnished valuable training stations for developing neophytes into full-fledged industrial hygienists. More recently, industry has been training chemists, engineers, and physicists for both specialized and general work in the field by giving them opportunities to work with trained industrial hygiene personnel.

The National Conference of Governmental Industrial Hygienists was organized in 1938 and has since furnished a valuable forum for the discussion of problems and experiences among this important group of industrial hygienists. The American Medical Association held its first Congress on Industrial Health in 1939

The American Industrial Hygiene Association was also organized in 1939, primarily as a specialized group to encourage and foster the exchange and dissemination of technical information in the basic sciences, such as chemistry, physics, mechanical engineering, and toxicology, as it applies to industrial hygiene. This organization held its first annual meeting in 1940. It became the nucleus around which industrial hygiene developed and gained recognition as a scientific profession. Its membership now includes both men and women from the several sciences and medicine who represent the many facets of this particular field of public health. Industrial hygiene has successfully withstood abortive efforts at absorption by both safety engineering and medicine. It borders on each of those fields, but differs in technique from both, and one of its primary functions is to get these two groups to work hand in hand. As long as men of the professional strength that has characterized the field since the early Twenties continue their interest, industrial hygiene will be likely to retain its identity as a separate and important part of public health. It has a specific job to do and the specialized training to do the job—a fact that is constantly becoming more widely recognized. In recent years the American Industrial Hygiene Association, the Industrial Medical Association, the American Association of Industrial Nurses, Inc., and the National Conference of Governmental Industrial Hygienists have found it to their mutual advantage to hold joint annual meetings and to work closely together, with a pooling of research findings and practical experiences.

Until 1936 the industrial hygiene activities of the United States Public Health Service were relatively minor and were confined largely to research of a medical and statistical nature. From 1928 until 1932 toxicological research, such as the study of the effects of solvents, vapors, and gases on guinea pigs, rats, rabbits, dogs, and monkeys, as well as the development of the peritoneal injection method for evaluating proliferative action of dusts, was farmed out to the United States Bureau of Mines. Under the able guidance of R. R. Sayers and W. P. Yant this research had become extensive and the Bureau of Mines was hailed by some of the chemical industries as an impartial, qualified research institute where industry could have relative toxicities determined in order that the manufacturer as well as the public might be intelligently guided regarding necessary precautions in the handling and use of chemical products. The studies were co-operative arrangements whereby industry absorbed costs connected with the study of their products. The amount of money involved began to be attractive and protests against "subsidizing" the government and research caused the project to be discontinued. Later federal funds were made available to the United States Public Health Service through the Social Security Act, whereupon extensive research investigations and a program designed to establish active industrial hygiene units in the health departments of the various industrial states were inaugurated. By 1941 the facilities of the Industrial Hygiene Division, National Institutes of Health, of the United States Public Health Service had been greatly extended, and the personnel had increased from less than a score of persons in 1933 to well over

200. Many of these qualified persons were loaned to various states to help them establish their own divisions of industrial hygiene, assist in training local personnel, and "sell" the entire field of endeavor to the local officials and population.

Prior to 1936 there were only five state departments of health and three state departments of labor conducting industrial hygiene activities, and these activities were limited. Under the impact of World War II and generous federal grants of funds all the industrial states established industrial hygiene units. In November, 1946, these totaled 52 units, spread over 41 states. The enormous increase in harmful situations along with demands for manpower conservation accompanying World War II made investigational industrial hygiene surveys very much in demand, and led to the hasty training of a number of men for this work. Many of these men had had only rudimentary training in the evaluation of exposures and little or no practical experience in control methods. However, because of, or in spite of, the efforts of this group of novices, and the relatively few seasoned men, industrial health was well promoted during World War II. Industrial health comparisons of munitions workers for 1917–18 and 1941–45, for instance, are striking. Under the stimulus of additional federal funds allocated to states and territories, the development of official industrial hygiene agencies reached an all-time high in 1949 and included all but two of the states.[3] This peak was in turn followed by a five-year period of retrogression necessitated by economy drives and appropriation cuts, during which about half of the trained personnel were absorbed by private enterprise and local health departments. In many instances they assumed positions of even greater responsibility in advancing industrial health objectives. The present rapidly mounting public and congressional interest in atmospheric pollution indicates that another swing of the pendulum is gaining momentum.

Other important organizations that have been active in the advancement of industrial hygiene include The American Standards Association, The Industrial Hygiene Foundation of America Inc., The John B. Pierce Laboratory of Hygiene (New Haven, Connecticut), The Saranac Laboratories (Saranac Lake, New York), life insurance companies as well as mutual and stock company compensation insurance carriers, and many of the larger private industries. Employee groups are also evidencing an active interest in industrial health. In 1945 a health institute was opened by the United Automobile Workers (CIO) in Detroit to give diagnostic service to union members. Employees no longer regard x-ray examinations or industrial hygiene surveys with the suspicion that was common a few years earlier. This change of attitude is due in part to improved practices, but mainly to educational successes; in short, the average employee now understands the purpose of such health-control work and realizes its value to his well-being. Some states now require pre-employment and periodic medical examinations for persons exposed to potentially harmful materials.

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[3] V. M. Trasko, *Am. J. Pub. Health*, **45**, 39 (1955).

II. World War II and Industrial Hygiene Service

Industrial hygiene procedures have largely passed through the period of inquiry into the causes of ill health and are now devoted to anticipating and avoiding harmful situations before they have time to cause injury. Many different organizations played a part in this rapid development during the period of expanded production in 1941–45.

A. OFFICIAL AGENCIES

The Army provided men to make surveys and recommend control measures in Army-owned and Army-operated industrial installations. Similar service was rendered to government-owned, privately operated munitions plants by other government industrial hygiene groups co-operating with the Army. The Navy provided men for its shore establishments, and co-operated with the Maritime Commission in providing service for private shipyards. The United States Public Health Service supplied funds and loaned trained personnel to state and municipal health departments, and also conducted field surveys in industry, especially munitions works. The United States Department of Labor concentrated upon activities of an educational nature. The United States Bureau of Mines greatly expanded its health program in relation to mining operations. During and following the period of reconversion to the manufacture of civilian goods many of the trained men who had been active in government agencies were reabsorbed by industry.

B. INSURANCE AND INDUSTRIAL GROUPS

Life insurance and compensation carriers were rather active in the field well before 1941, and they continued their work as best they could despite the inroads into their personnel from all sides that occurred during the war-production years. Later they expanded their activities and re-employed trained men.

During this period industry became much more active in the field than formerly, partly because of a newly awakened interest as a result of state and municipal activity, partly as a result of organized labor's demands for healthful working environments, partly as a hedge against racketeering, but largely because of a desire on the part of management to make the working environment healthful and attractive. This came about not purely from an altruistic attitude but because management began to realize that the maintenance of a healthful environment pays dividends from the cost-saving viewpoint as well as in employee satisfaction and reduced turnover of the labor force. More and more industrial concerns have come to the conclusion that industrial hygiene is a necessary adjunct to production and not something to be entrusted entirely to overworked government agencies.

Private institutions, such as, for instance, The Industrial Hygiene Foundation, encountered greatly expanded demands for their services during this period. Other foundations such as the Air Pollution Foundation and the National Sanitation Foundation later developed programs pointed toward air- and stream-pollution evaluation and control.

C. EDUCATIONAL INSTITUTIONS

Those colleges that had given any organized instruction in industrial hygiene prior to 1940 now provided short courses for greatly expanded classes in an effort to give a large number of interested persons sufficient knowledge to make them useful workers in the field during war-expanded production. During and following this period many medical schools set up short courses in industrial medicine and hygiene as orientation and refresher courses. A few institutions of advanced learning have provided special instruction in health and safety. The present plans include advanced training and education leading to degrees in health and safety engineering, and the opportunities for advanced instruction for chemists, physicists, mechanical engineers, and others who wish to prepare themselves for industrial hygiene engineering are improving.

A report[4] of the Committee on Professional Education of the American Public Health Association lists Columbia, Harvard, Johns Hopkins, Toronto, Yale, and the state universities of California, Michigan, Minnesota, and North Carolina among the institutions accredited to give the degree of master of public health for the academic year 1946–47. This report recognizes the basic sciences underlying public health practices, including industrial hygiene. Therefore, all graduates of these schools presumably will have received at least a good orientation course in industrial hygiene; some may have an opportunity to prepare for later specialization in it. A proposed report on educational qualifications of industrial hygiene personnel was published at the request of the above-named American Public Health Association Committee.[5] As the reservoir of competent, experienced industrial hygienists grows, we hope for a greater number of qualified teachers of the subject in order that more students may be encouraged to specialize in the field and thus fill the growing needs of industry and official health and accident control agencies for such specialists.

There has been concurrently a movement to provide advanced courses in technical safety and hygiene for graduates of the arts and sciences independently of any medical or public health schools. The ultimate result of such instruction, if extensive, would be expected to be a merger of safety and industrial hygiene into something yet to be named. That there is opportunity for such academic instruction is apparent but there have been much hesitation, uncertainty, and bickering about its initiation. This has been due in the past to a dearth of suitable text material and qualified faculty, as well as a division of opinion regarding the scope of the field and the aims to be fulfilled.

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[4] Committee on Professional Education, *Am. J. Pub. Health*, **36**, 244 (1946).

[5] Committee on Professional Education, *Am. J. Pub. Health*, **44**, 1197 (1954).

D. RESEARCH ORGANIZATIONS

Much research into the toxicity of materials and into methods of analysis and control of harmful exposures was conducted during World War II by the United States Public Health Service, and some by industry. Several industries, seeing the need for such research, made plans to enter the field following the return to peacetime activities. The need for research into the cause and effects of many uncharted forms of air pollution is great. Such work can never expect to keep pace with industrial development, the manufacturing chemist, and the even faster moving physicist, but can follow more closely than has been done in the past. Moreover, the individual homeowner needs to be made more aware of his contribution to a rapidly growing air-borne waste disposal problem.

III. Industrial Hygiene in Foreign Countries

The best insight into what European countries are doing in industrial hygiene is given in material regarding toxic limits and industrial health in wartime published by the International Labour Office. According to reports, the rules and regulations in these countries concerning the use of poisonous materials in industry are based on the results of periodic medical examinations of the workers in plants handling such substances. At certain intervals prescribed by regulations the worker must be examined by a physician. It is the task of the physician to *make an early diagnosis to recognize and evaluate the first signs of absorption of a poison* and if necessary to remove men from work temporarily. The ILO believes that this is a reliable method for the timely detection of endangered workers and also of the hazards in a specific plant. The shortcomings of such a plan of approach obviously are in evaluating the first sign of absorption—a trick physicians in the United States have not been able to turn to their complete satisfaction. The toxic materials that give rise to recognizable, specific, dependable clinical signs in advance of serious injury are disappointingly few.

The ILO report points to the lack of compulsion in the United States regarding periodic medical examinations. There is little room to doubt that regular and more frequent medical examinations are a desirable way of discovering dangerous exposures, especially in the absence of competent industrial hygiene engineering evaluation and control. When the two methods are properly co-ordinated, however, the most dependable safeguard against harmful exposures is provided.

A. ENGLAND

In England the medical phases of industrial health have received more attention than the more technical and engineering phases of evaluation and control. Some support for this opinion is seen in the report of foundry experience.[6] Only 150 sandblasters were engaged in steel foundries prior to the war, yet 31 sandblasters were given certificates covering death, total disablement, or suspension on account of silicosis in the 1932–42 period. Congestion of operations, due to great demands on capacity, has been credited with increasing the number of silicosis cases by raising the concentration of dust-producing operations per unit of shop area. A committee appointed to study the situation recommended: (*1*) no silica should be used in parting compounds; (*2*) no sand should be used as an abrasive in "sandblasting"; and (*3*) no person under 18 should work as a sandblaster, in repairing a sandblast plant, or within 20 feet of such a plant. Consideration was given to prohibiting the use of free silica in molding material as well as silica paint on cores. Certain of these regulations appear unnecessarily drastic and do not take into account the possibilities of engineering control.

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[6] Dust in steel foundries, *Engineering (London),* **158,** 152 (1944).

E. R. A. Merewether, Senior Inspector of Factories in England, recognized this lack of engineering interest and skill when in 1942 he told an American Public Health Association audience that the time had arrived when "the doctor no longer knows everything about everything" and conceded American leadership in industrial hygiene engineering. Merewether urged the English chemists to instigate the formation of a society for "the holding of annual conferences and the publication and distribution of papers and literature on the subject of industrial health and safety,"[7] much as is done by our own American Industrial Hygiene Association and to a limited extent by the American Public Health Association. The British Occupational Hygiene Society was established on April 27, 1953, and held its first conference in November of the same year.

B. RUSSIA

C.-E. A. Winslow, who visited Russia in 1917 and again in 1936, reported major advances in public health in that country. Emphasis had been placed on the health of industrial workers. Scientific studies of many occupational hazards and of means of promoting industrial health have been conducted by various research organizations, of which may be mentioned the Institute of Industrial Diseases in Moscow, the Central Institute for Nutrition in Moscow, Pavlov Institute, the Leningrad Institute of Safety, Hygiene and Technique, and States' Scientific Institute of Labor Protection.

The Soviet state has given special attention to questions involving better labor conditions, looking toward the highest possible efficiency and production, as well as the mental and physiological well-being of the workers. Early permissible standards for air pollution in factories tended to be ultraconservative on the side of safety, and rather severe standards for industry to meet. Various motives have been suggested as having contributed to the zeal of industrial hygiene investigators. Later, however, some standards were modified to conform with experience, and there have been indications that in general the requirements have been made somewhat less rigid.[8] For instance, the maximum limit for carbon monoxide was

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[7] *Chem. Age (London)*, **53**, 353 (1945).

[8] A. Metsatunyan, *Hyg. and Sanit. (USSR)*, **10**, 23 (1943).

0.02 mg. per liter, and is now 0.04 mg. per liter (approximately 35 p.p.m.), methyl alcohol was 0.03 mg. per liter and is now 0.07 mg. per liter (approximately 52 p.p.m.), ethyl alcohol was 1.0 mg. per liter and is now 1.5 mg. per liter (approximately 800 p.p.m.). Amyl and other alcohols, however, that were 1.0 mg. per liter are now 0.5 mg. per liter (approximately 280 p.p.m. amyl alcohol and 330 p.p.m. butyl alcohol). This trend, along with our own general trend downward, indicates that we may possibly reach common ground for some if not most of our thinking in regard to what constitutes a permissible and what a potentially harmful exposure. The disparity of standards for outdoor air may be somewhat greater.[9] We have seen good information resulting from research into the control of industrial health in Russia and we hope to see the iron curtain lifted sometime in the future. A free exchange of ideas among all countries regarding industrial hygiene is sure to benefit each participant.

C. GERMANY

In Germany in the year 1928 the task of collecting material and making practical observations in industrial hygiene was entrusted to the Medical Committee of the German Society for the Protection of Labor. A literature search was conducted as well as experimental investigations of the most important organic solvents. The German Health Office was established as a clearing house for information regarding chemical composition of solvents and the etiological factors of illness resulting from their use. The inspectors of factories were men with medical training but without engineering training, and as a result the control measures were largely of a medical nature. It has been stated by one of these factory inspectors that it was easier and more routine to obtain biological specimens, including blood samples, from workmen than to obtain samples of air. The literature on the results of pharmacological and toxicological investigations, upon which much of our present practice is based, is replete with such names as Flury, Führer, Koelsch, Köster, Lehmann. Müller, Wirth, Zanger, and Zernik. Priceless instrumentation, records, and intellect have been reported lost as a result of World War II. Many rules and regulations for industry have been developed over the years and are presently applied in West Germany to the use or manufacture of certain chemicals, the conduct of specific operations, or workrooms below ground. These numerous regulations are pointed toward medical examinations and mechanical safeguards for the control of any exigency rather than toward the engineering control of the environment to conform with hygienic standards. The regulations are enforced by a host of factory inspectors.

D. OTHER COUNTRIES

Not only have many of the countries of Europe, Asia, and Latin America sent selected personnel to study industrial hygiene techniques in the United States and Canada—whose progress is somewhat similar to our own—but several of them have set up training centers at home. One of the most notable is that established at Lima, Peru, with the co-operation of the Institute of Inter-American Affairs.[10] Japan has established an Industrial Hygiene Association. There is ample evidence of a widespread and growing interest in industrial hygiene and health engineering in nearly all countries.

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[9] V. A. Riazonov, *Sanitary Safeguarding of Atmospheric Air.* Moscow 1954. Reviewed by F. S. Mallette, *Smog News (ASME),* No. **54,** 2 (November 30, 1955).

IV. Industrial Hygiene in the United States

We have seen that the United States lagged behind other countries in providing control measures or compensation for occupational diseases, and that it was not until the late Twenties that industrial hygiene became more than an incipient dream in the minds of a relatively few individuals. A few farsighted pioneers in the field of public health saw the possibilities of making the control of industrial health a vocation and of enlisting the technical aid of professions other than medicine to do the job. Industrial hygiene in the United States has from the start been kept on a high professional plane and has therefore attracted men with a liberal leaning toward technical research.

One of the outstanding reasons that industrial hygiene has been so successful in controlling adverse environmental conditions and in preventing or controlling occupational disease is that pronounced rivalry has developed between the medical men and the men of the sciences, as well as between the scientific professions involved, for instance, chemists and mechanical engineers. This rivalry, as has been pointed out before,[11] has been wholesome and has resulted in advancing accomplishments in the field of industrial health that would have been improbable without it; competition and wholesome incentive have always inspired accomplishments. Advances in industrial process ventilation have been almost solely the achievement of the industrial hygienist: the heating and ventilating engineers, either from lack of interest or understanding, have remained aloof. As a result, many grotesque ventilating systems and ideas have appeared under the sponsorship of sheet-metal men who did not even pretend to understand the physical laws applying to air flow and air movement but were attempting to supply a demand for protection of workmen as best they could.

V. Prospective Roles of Industrial Hygiene

Industrial hygiene has laid aside its swaddling clothes and entered a vigorous stage of advancement. It is no longer seen by industry as the aimless effort of intellectuals collecting bottles filled with nothing so that they can prepare long and useless discourses that few would read or understand, or, if they did understand, would know what action to take. The safeguarding of industrial health is on a business basis of evaluation and control and is recognized as such by both labor and management. The purpose of the industrial hygienist is no longer merely to "lock the stable door after the horse has been stolen" but to anticipate and prevent harmful situations, or to control them before serious injury results.

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[10] J. J. Bloomfield and A. S. Landry, *Am. Ind. Hyg. Assoc. Quart.*, **16**, 65 (1955).

[11] C. D. Selby, *Am. J. Pub. Health*, **30**, 1422 (1940).

The industrial hygienist has done much toward bringing medicine and safety engineering into close co-operation, partly because his interests overlap these two fields. For instance, the safety engineer looks to the industrial hygienist for assistance in problems involving the technical phases of the flammability or explosibility of solvents, gases, vapors, and dusts. Likewise, the technical differences between the classes of respiratory protection devices and the chemical absorbents used are somewhat confusing and require special study. Medical men with no engineering experience, on the other hand, will be more concerned with the toxicological aspects and in their desire to prevent harmful exposures may consider only the promotion of health without due regard for practical economic measures or the problems of the plant production and maintenance engineers. It is the industrial hygienist's job to become acquainted with these engineers and get the benefit of their reactions to any of his major recommendations so that his control measures will be more sound and acceptable. One of the most urgent needs today is a common understanding between the heating and ventilating engineer and the industrial hygienist. The former thinks in terms of comfort and air conditioning and frequently is unable to grasp the problems involved in the control of gases, vapors, and dusts, which are designated in parts per million or million particles per cubic foot. The industrial hygienist is going to have to take the initiative in getting his control recommendations into terms of volume or rate of flow or something more familiar to the heating and ventilating engineer. He should make it understood more generally that the control of all air contaminants, even excess heat, is something the heating and ventilating engineer needs to become acquainted with and reckon with—not a thing to be added as an afterthought or left to be planned by unskilled persons who may thereby upset the functioning of an otherwise carefully planned heating and ventilating or air-conditioning installation.

Then there are the architects, the plant layout men, and building designers as well as the designers of machine tools and equipment. The basic principles of industrial hygiene must be presented to these men so that industrial hygiene will start with the blueprints of factories and machines. All too frequently still industrial hygiene becomes a matter of telling management what their mistakes have been and how many tremendously expensive changes will have to be made, rather than getting these ideas into design where the most good will be accomplished easily and cheaply.

In one of the most modern aluminum foundries built during World War II, one frequently pointed out as a model of perfection, the mechanization was excellent, the sand-handling and dust-control equipment was good, but some fume, smoke, and heat sources were uncontrolled and the general ventilation left much to be desired. No one had ever made the designer aware that dust- or fume-laden and heated air had to be moved out of any enclosure by removing all of the contaminated or heated air. He had provided ample air supply and exhaust but the inlet and exhaust ports were both in the relatively flat roof and they terminated at the ceiling so that the air at the ceiling was given an ineffectual churning while fumes and smoke from pouring, cooling, and other incidental unhooded operations were but slowly cleared away. Obviously, smoke and fumes should have been removed at their sources and the make-up air should have been distributed at or near the floor level so that contaminated and heated air would have been displaced upward and exhausted through ports in or near the ceiling. Estimations of the cost of remedying the condition exceeded the cost of the original ventilating system, but strangely enough the same error is still widespread today.

Until all schools of higher learning take up the teaching of some of the fundamentals of industrial hygiene in their engineering and other professional courses, the burden of this job will rest on the hygienist. This responsibility applies not only to plant design, but to machine design and plant layout as well. The opportunity to review plans should be sought in an effort to improve design so as to promote the correct application of all control measures, where such has not been done. Not only harmful exposures but also dirty occupations are on the way out. The workingman has come to expect and demand a safe, healthful, and relatively clean and stress-free work place, and, having once worked in such surroundings, will not readily return to an excessively dangerous or dirty occupation. Widespread shifting of labor during war production resulted in acquainting many workmen with the fact that control of the work environment is possible. Even the foundry has undergone a transmutation from a place with a dirty, dusty, smoke- and fume-filled atmosphere to one of comparative cleanliness. We have some of the cleanest work places in the world here in the United States. We also have some that we do not care to talk about—they are the ones upon which we should focus our attention until they have been cleaned up. American industry is aware of the benefits of more and better production derived from environmental control and health-promotional activities and needs only to be guided in their application.

Will industrial hygiene engineering be absorbed by either the medical profession or by safety engineering? The idea is not a new one and the answer is in the field of astrology, which to date strangely enough has not been proposed as an essential factor in the promotion of industrial health. Anything can happen and if our educational institutions can turn out doctors of medicine who are accomplished in the sciences of chemistry and mechanical engineering, mathematics, and physics, yet who are willing to do the amount of plain drudgery associated with the engineering phases of the prevention of occupational diseases, then industrial hygiene will surely become the sole province of medicine. If, on the other hand, academic instruction in our engineering and other professional courses allied with this field adequately provides the principles and practice of industrial hygiene and safety, the trend will be toward the development of more competent and highly trained personnel to cover both of the fields now considered separately as industrial hygiene and safety engineering. For such instruction to be successful it must necessarily provide a sufficient period of supervised practice in industry. Graduates of such courses would find common ground and interests with the industrial physician of the future who will appreciate more and more the nature and value of engineering control practices that augment and simplify, in many cases are essential to, his own goal of preventive medicine and hygiene. Regardless of where or how it is taught—in medical schools, engineering schools, colleges, or trade schools—the engineering control of industrial health is sufficiently important to warrant its being placed on the same plane as civil, chemical, or other engineering courses. It should encompass a well-planned curriculum to include evaluation of the environment, toxicology, pharmacology, physiological effects, control methods including the principles and practice of ventilation, and the correction of all adverse environmental factors—not a course that can be picked up as an afterthought in the last semesters or as a three-month "refresher" course.

Neither of these changes is likely to be brought about overnight or to affect large numbers of persons immediately. Those now in the fields of industrial hygiene or safety who have a broad understanding of their problems need have no concern about such a change. Those who do not have a broad viewpoint should perhaps lose no time in acquiring it or in finding a more dependable future. Meantime we continue as we are. More schools are choosing their students from many professions and directing their instruction to the specialized field of industrial hygiene on the graduate-student level much as the Harvard School of Public Health has done, with the result that industrial hygiene will doubtless retain its identity and continue to work co-operatively with the medical and safety groups.

CHAPTER II

Industrial Hygiene Records and Reports

RUTH B. PATTY

I. Introduction

Industrial hygiene is pre-eminently an American approach to the problems of occupational diseases and the health of industrial employees. In control of hazardous situations it has made remarkable strides in the past quarter century. Whether the statistical data necessary for proper appraisal of successes, failures, and additional needs and for appropriate action have kept pace with technical know-how is debatable. In the eyes of one of our English colleagues, Mr. Bryan Harvey, an inspector of factories who did graduate work at Harvard University:

> It [American industrial hygiene] shows great energy and drive and the marked characteristics of the vigorous private enterprise that so largely supports it. It lacks, to English eyes at least, coordination. What state control there is, is of 48 different varieties. . . . In particular, they lack national accurate statistics of the incidence and morbidity of industrial disease. While one may well be lost in admiration for the forceful and painstaking efforts which industrial hygiene is making to control the industrial environment there is little accurate data by which to judge its success.[1]

Nearly all data begin with either records or reports. Both, to be of value, must be accurate, complete, appropriate, and at the same time as concise as possible. Records should be readily accessible. There are many reasons for keeping records applicable to industrial hygiene activities. A large number of them are intended to provide, at some future date, information on the individual and the influence of his working environment upon him from the date he was hired. Records of an employee's pre-employment and periodic medical examinations as well as studies of his industrial environment, either periodically or in continuous recording, are of this class. One aspect, which points up the great need for accuracy and specificity here, is the fact that any or all of these records could become part of a court case. If this should occur it might be necessary for the person who actually prepared the record to testify regarding it.

Another purpose in keeping records is to develop a basis for a statistical analysis of the effect of the environment on groups of persons: to provide an evaluation of toxicities of materials in the environment and a guide for control measures where needed. Records of industrial hygiene surveys usually have this as their primary purpose. Occupational disease reports to the states (see Figure 1) and claims filed for workmen's compensation also can be valuable in this way. Frequency and disability rates by occupational disease cause, most often compiled by insurance carriers or large industries, can be of much value here, particularly if sex, age, and specific occupational duties have been included.

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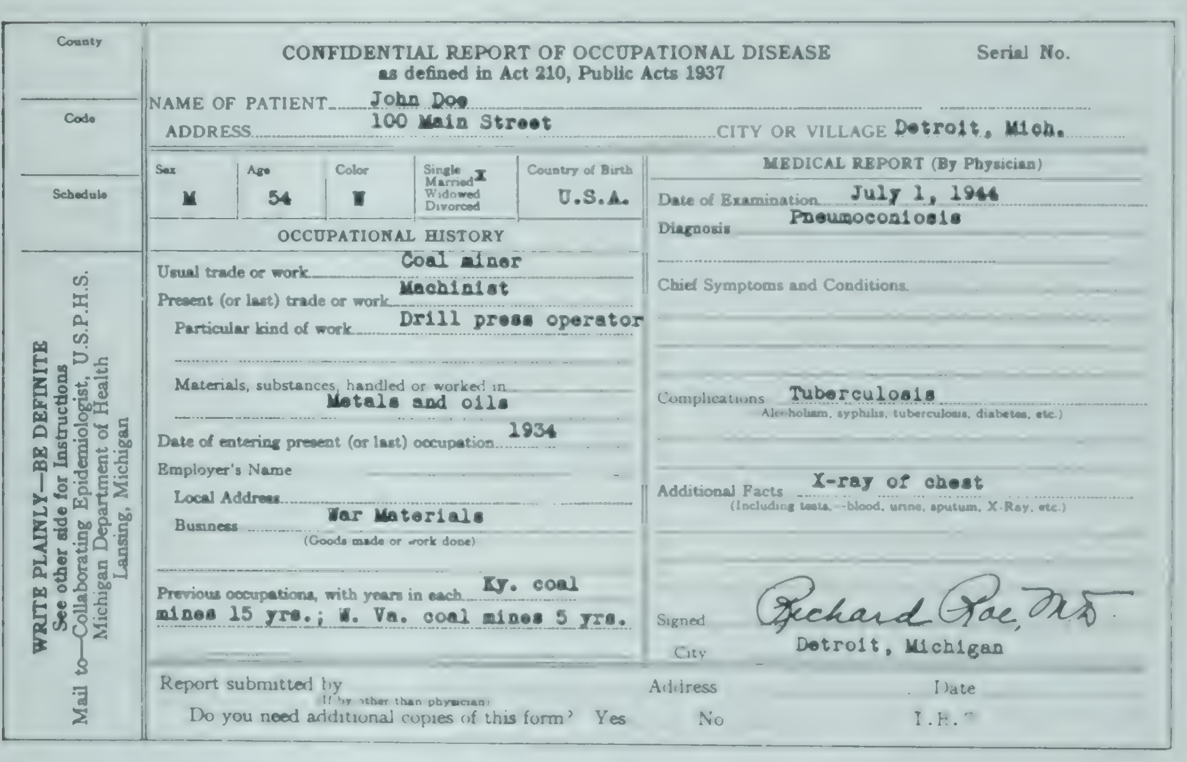
[1] B. Harvey, Some personal observations on industrial health in the United States of America, *Brit. J. Ind. Med.,* **11,** 222 (1954).

No one set of forms and records can be adapted to every industrial hygiene organization, although the general ideas are the same. A set of record forms that is ideal for a large plant may prove entirely unsatisfactory for a small plant, or for a company that operates a number of scattered and diversified plants. Insurance companies and state or city industrial hygiene divisions will require special records for correlating their contacts with every type and size of industry. In this chapter are presented typical problems that arise and forms that have proved useful to different industrial hygiene organizations in the past. The reader should adapt these or other forms to his particular needs.



County

Code

Schedule

WRITE PLAINLY—BE DEFINITE
See other side for Instructions
Mail to—Collaborating Epidemiologist, U.S.P.H.S.
Michigan Department of Health
Lansing, Michigan

CONFIDENTIAL REPORT OF OCCUPATIONAL DISEASE
as defined in Act 210, Public Acts 1937

Serial No.

NAME OF PATIENT John Doe
ADDRESS 100 Main Street CITY OR VILLAGE Detroit, Mich.

Sex	Age	Color	Single [✓ Married] Widowed Divorced	Country of Birth
M	54	W		U.S.A.

OCCUPATIONAL HISTORY

Usual trade or work Coal miner
Present (or last) trade or work Machinist
Particular kind of work Drill press operator
Materials, substances, handled or worked in Metals and oils
Date of entering present (or last) occupation 1934
Employer's Name
Local Address
Business War Materials
(Goods made or work done)
Previous occupations, with years in each Ky. coal mines 15 yrs.; W. Va. coal mines 5 yrs.

MEDICAL REPORT (By Physician)

Date of Examination July 1, 1944
Diagnosis Pneumoconiosis
Chief Symptoms and Conditions
Complications Tuberculosis
(Alcoholism, syphilis, tuberculosis, diabetes, etc.)
Additional Facts X-ray of chest
(Including tests,—blood, urine, sputum, X-Ray, etc.)
Signed Richard Roe, M.D.
City Detroit, Michigan

Report submitted by Address Date
(If by other than physician)
Do you need additional copies of this form? Yes No I.H.-7

Figure 1. Occupational disease report.

II. Types of Plant Records

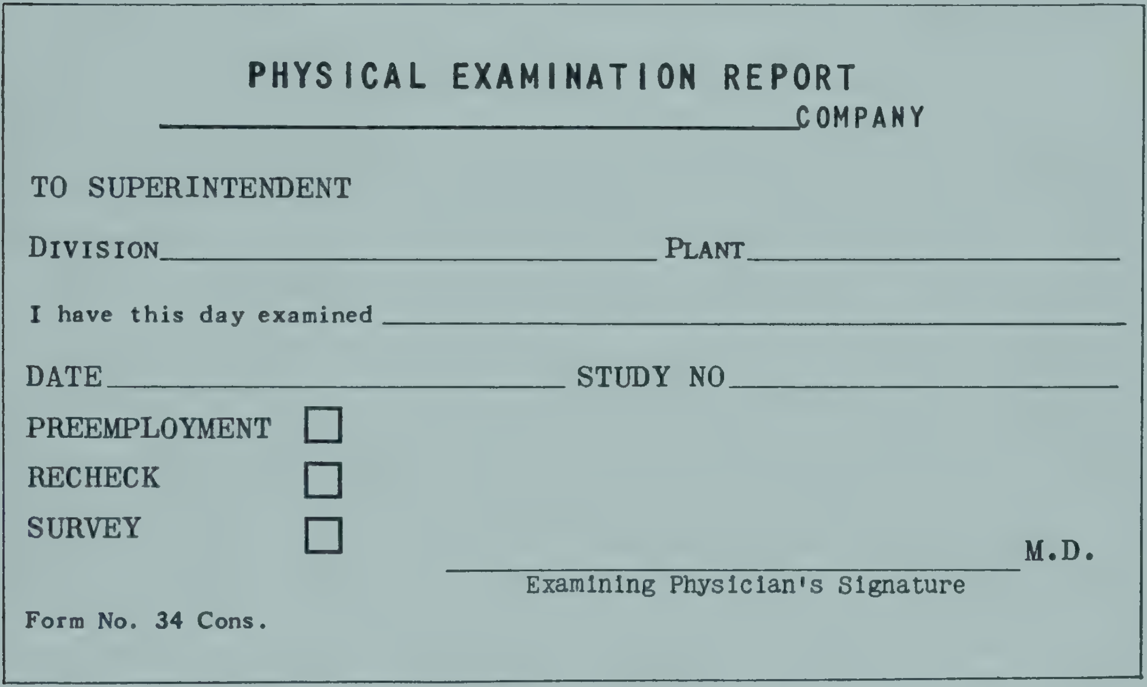
In any large industrial organization there are seven classes of records that can be of value to the industrial hygiene department. These are: (1) records of the environment, (*2*) medical examination records, (*3*) the nurse's records, (*4*) records of biological specimens, (*5*) safety records, (*6*) personnel records, and (*7*) compensation claim records.

A. RECORDS OF THE ENVIRONMENT

These records are the specific responsibility of the industrial hygiene department. They are collected, analyzed, and filed in the department, regardless of to whom else they may be presented for appropriate action. They will be discussed at length later in this chapter.

B. MEDICAL EXAMINATION RECORDS

Certain medical records are vital to industrial hygiene. The ideal medical program includes a complete pre-employment examination with chest roentgenogram, both of which are repeated at regular intervals in plant surveys. In both, the medical findings with respect to the individual are kept confidential, the information being available only to the medical department and the plant physician. The individual is advised of the results of his examination, but the plant management is not informed.



PHYSICAL EXAMINATION REPORT

______________________________ COMPANY

TO SUPERINTENDENT

DIVISION______________________ PLANT______________________

I have this day examined ______________________________

DATE______________________ STUDY NO______________________

PREEMPLOYMENT ☐

RECHECK ☐

SURVEY ☐

______________________________ M.D.

Examining Physician's Signature

Form No. 34 Cons.

Figure 2. Physical examination record.

However, as one of the main objectives of these examinations is the proper placement of the individual in industry, there must be some simple means of advising management where a man may work. One simple way of handling this is by a color card system, an example of which is shown in Figure 2. The card states merely that John Smith was examined on a certain date. If the card returned to the personnel department and thereafter kept in its files is green, the man is physically suitable for any job in the plant. Should the card sent back be yellow, it means that the subject has some defect or handicap that must be considered, and the personnel department is required to discuss the proposed job with the physician and medical department to determine whether the individual may fill it without harm to himself or others. A yellow card in this man's record also means that he may not be transferred without consulting the medical department and obtaining its permission. A man may have a yellow card just temporarily, until some defect is corrected. A red card is returned for men exhibiting serious conditions, such as complicated silicosis, heart disease, and uncorrectable vision deficiency. Applicants getting a red card may not be hired except for work in special nonhazardous situations. Old employees so classified on surveys are treated the same as men with yellow cards and some position is found compatible with their condition.

The usefulness of an industrial hygiene department is greatly augmented by close collaboration with the medical department, mainly through comparison of records compiled by each. Where an industrial hygiene survey shows high dust counts, comparison of results with chest studies, particularly if there are employees with long service records in the department, can help in determining whether the condition should be attacked as a true occupational disease hazard or as a nuisance. If management is approached with all the facts, hysteria is avoided and better confidence is fostered.

Similar situations develop where medical findings can be elucidated by consideration of industrial hygiene findings. An example was the finding of a high percentage of chests that appeared silicotic in an x-ray survey, but in this case the dust counts were only moderate and the free silica concentration was very low. Further study showed very high concentrations of iron oxide, mainly as fume too small to count, from welding and cutting operations. This pointed to a diagnosis of "possible iron pigmentation" as described in the work of Sander.[2]

C. NURSE'S RECORDS

The plant nurse's records are of vital interest to the industrial hygiene department. Every employee's visit to the nurse, whether for actual injuries and re-dressing or for other complaints, such as headache, cold, or sore throat, should be recorded and recapitulated by department each week or month. A critical review of these records by the industrial hygienist may uncover a previously unsuspected atmospheric contamination, such as carbon monoxide from a defective flue, giving rise to an unusual number of headache complaints from the area affected. Even more obvious is this review as a means of picking up new sources of dermatitis, for as soon as a material that is an active skin irritant is introduced, the nurse will be deluged with complaints. In such acute conditions the alert nurse will call in the industrial hygienist before the situation has gone very far.

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[2] O. A. Sander, *J. Ind. Hyg. Toxicol.*, **26**, 79–85 (1944).

A medical records training program for nurses in one large industry consisted of the following seven sections. It shows keen appreciation of the importance of having records of the highest possible quality.

Unit 1: The Importance of Concise, Neat, Accurate, and Complete Reports. An attitude building session aimed at the development of a greater appreciation of responsibility for and importance of good medical records.

Unit 2: How to Get the Most Out of an Interview. A session aimed at developing a better understanding of the principles and techniques of conducting an effective interview.

Unit 3: Conducting Better Interviews. A series of sessions designed to increase interviewing skills in realistic, local plant situations.

Unit 4: Review of Medical Terminology and Anatomical Locations. A session or two conducted by the doctor aimed at refreshing the nurse's knowledge of medical terminology and anatomical locations.

Unit 5: How to Properly Record Data. A series of sessions devoted to a study of the local plant forms and proper methods of completing these forms.

Unit 6: Recording the Data. A series of skill development sessions designed to aid the nurse in consistently producing high quality medical records.

Unit 7: Evaluation and Summary of Program. A review and summary unit aimed at aiding the nurse to develop a continuing program of self-improvement.

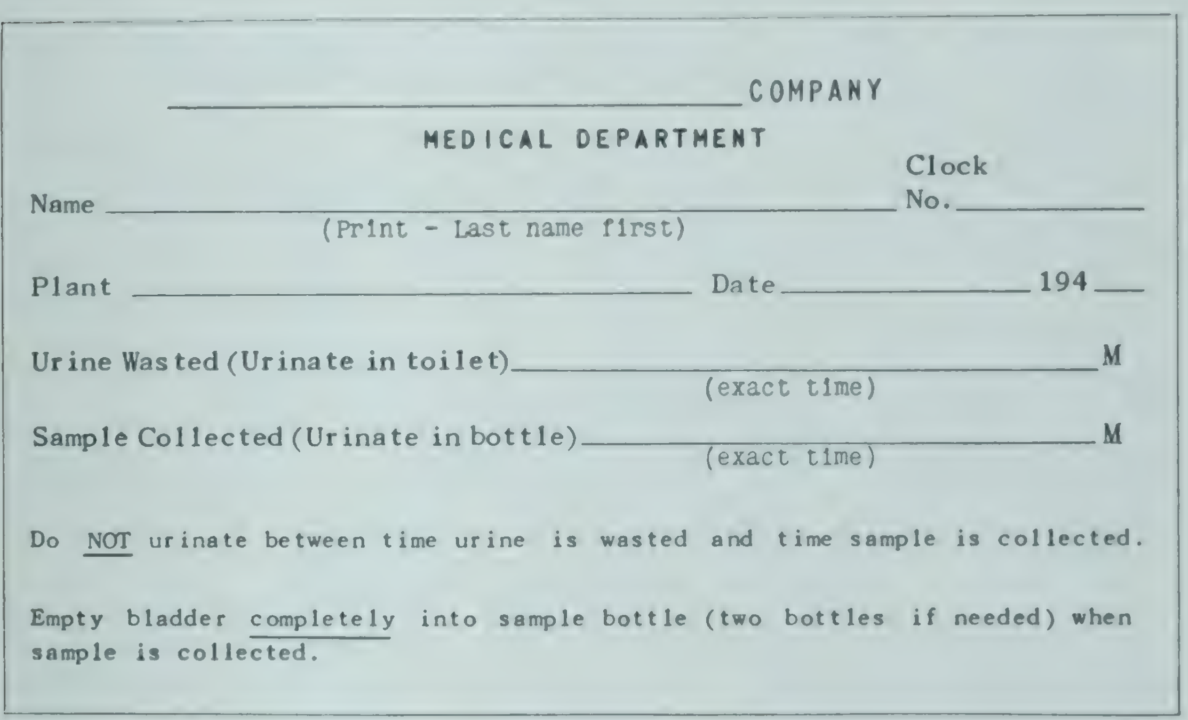
D. RECORDS OF BIOLOGICAL SPECIMENS

When the effect of the environment is measured directly, as by analysis of spot urine samples for lead, a means is provided of correlation of studies of the environment and of the individual. The following is a description of such a survey made in a program for controlling the lead hazard in a brass foundry at some distance from the industrial hygiene laboratory.

Spot samples were collected in the first-aid room at the plant, and the card shown in Figure 3 was filled out and fastened to the bottle with a rubber band. This card is the result of simplification after first using a three-part slip that had to be filled out with two carbon copies. The first form was abandoned because it required too much time on the part of the plant personnel and was not easily understood. It also required for each sample collected filling in information that was already available to the laboratory even when the first sample had been collected, such as the age of the individual and his working place. Also it had spaces for laboratory data, which were not pertinent to the phase of the survey made at the plant.

Simplicity and explicitness must be the keynote of a form such as this, which is to be filled out by plant personnel. Use of the term "Urine Wasted" had caused some confusion; therefore, the explanation "Urinate in Toilet" was added. The purpose here, to obtain a record of *all* of the urine excreted by the kidneys for a *definite period* with information as to person, place, and time, is the one and only function of the card.

In the laboratory it is necessary to correlate the data on this card with the volume, analytical procedure (polarographic, dithizone, and so on), and results—information to be retained in the files for a limited period for reference in the event that a question as to the results should arise. A mimeographed columnar form was used and the data were entered in pencil, red being used where there was any divergence from the normal technique.



____________________ COMPANY

MEDICAL DEPARTMENT

Name ____________________ Clock No. __________
(Print - Last name first)

Plant ____________________ Date __________ 194 ___

Urine Wasted (Urinate in toilet) ____________________ M
(exact time)

Sample Collected (Urinate in bottle) ____________________ M
(exact time)

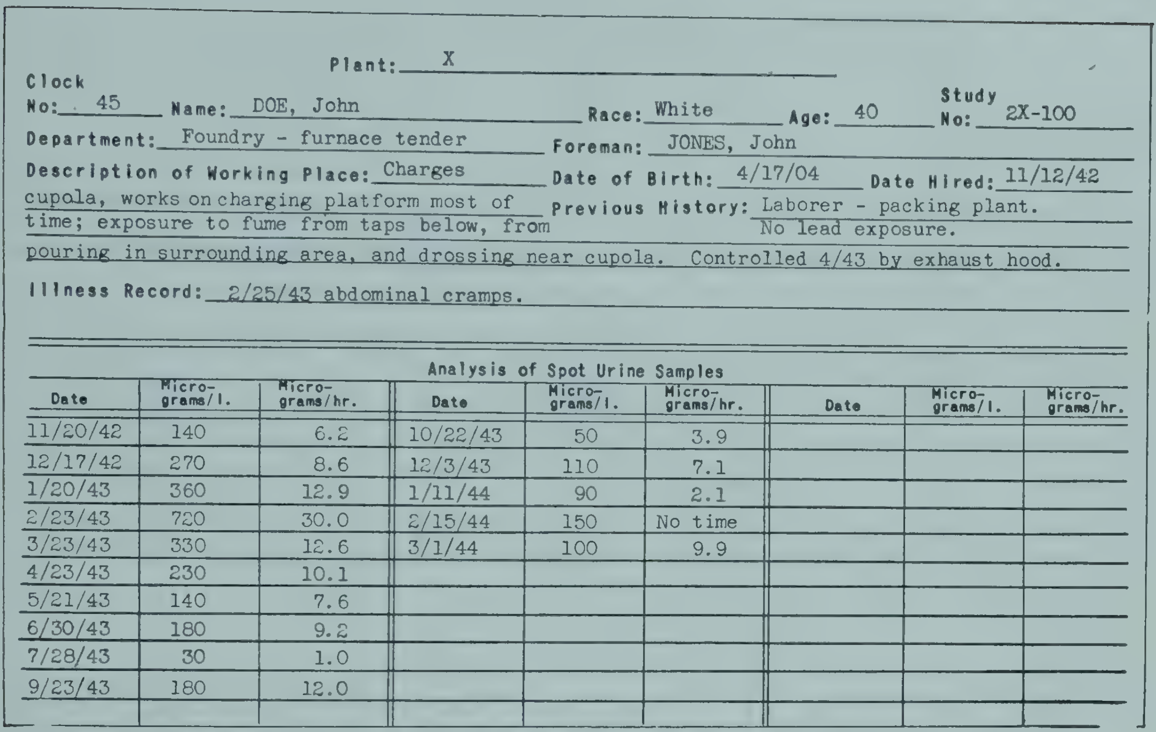
Do NOT urinate between time urine is wasted and time sample is collected.

Empty bladder completely into sample bottle (two bottles if needed) when sample is collected.

Figure 3. Urine sample record.

A permanent record of the findings on each individual is kept in the industrial hygiene department, with a duplicate in card form at the plant for the convenience of the local doctor (see Figures 4 and 5). Here all pertinent data on the individual and his environment are assembled, with records of the analyses that show the effect of his environment upon him. The graphic record on the back of the card shows the trend at a glance, whether favorable or unfavorable. With these cards available, statistical analyses can be undertaken and medical control facilitated. For instance, all the individuals in the plant can be segregated into groups for study of the trends in any one department or building or men with different lengths of exposure may be separated for comparison.

As the work of improving the environment progresses, study of these cards affords a means of determining whether—and where—the sampling should be continued and where reduced to quarterly or semiannual intervals. As the results are reviewed each month, any unusual conditions are obvious and the industrial hygienist can take steps at once to find the cause and provide relief.



Plant: X

Clock No: 45 **Name:** DOE, John **Race:** White **Age:** 40 **Study No:** 2X-100

Department: Foundry - furnace tender **Foreman:** JONES, John

Description of Working Place: Charges cupola, works on charging platform most of time; exposure to fume from taps below, from pouring in surrounding area, and drossing near cupola. Controlled 4/43 by exhaust hood.

Date of Birth: 4/17/04 **Date Hired:** 11/12/42

Previous History: Laborer - packing plant. No lead exposure.

Illness Record: 2/25/43 abdominal cramps.

Analysis of Spot Urine Samples

Date	Micro-grams/l.	Micro-grams/hr.	Date	Micro-grams/l.	Micro-grams/hr.	Date	Micro-grams/l.	Micro-grams/hr.
11/20/42	140	6.2	10/22/43	50	3.9			
12/17/42	270	8.6	12/3/43	110	7.1			
1/20/43	360	12.9	1/11/44	90	2.1			
2/23/43	720	30.0	2/15/44	150	No time			
3/23/43	330	12.6	3/1/44	100	9.9			
4/23/43	230	10.1						
5/21/43	140	7.6						
6/30/43	180	9.2						
7/28/43	30	1.0						
9/23/43	180	12.0						

Figure 4. Urinary lead record (front of card).

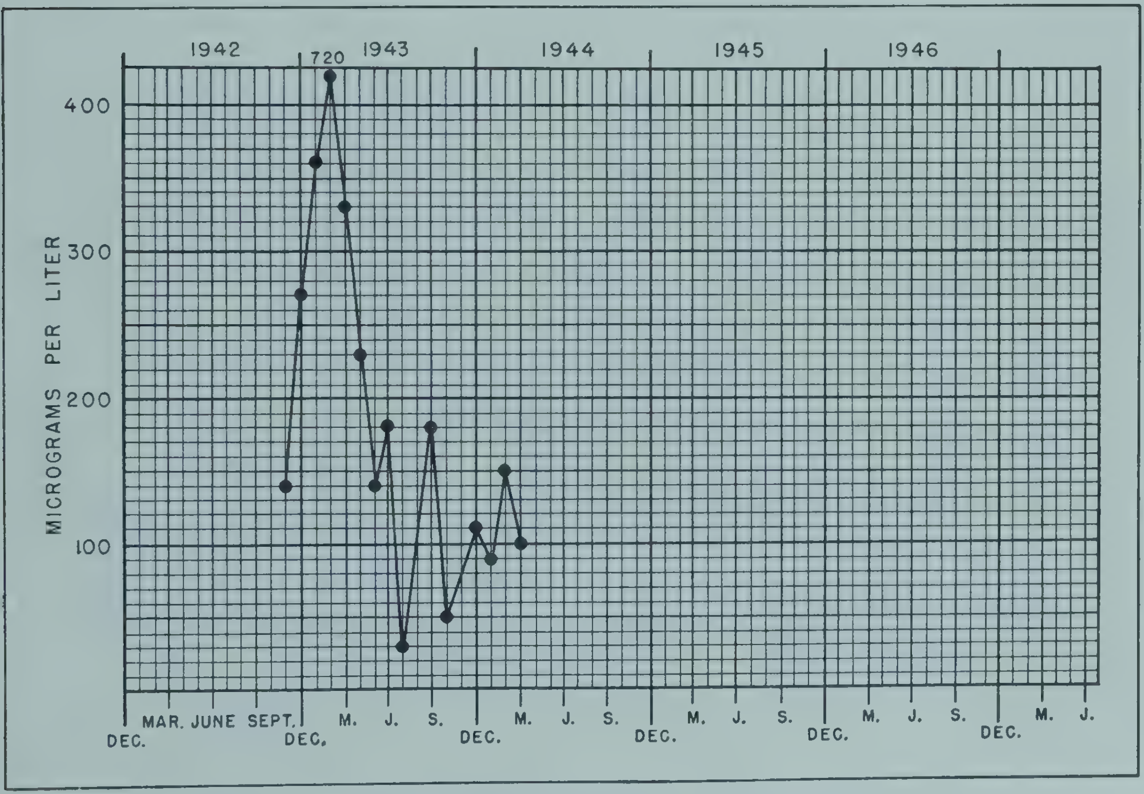


Figure 5. Graph of urinary lead record (reverse side of card).

An analogous program, the analysis of blood specimens for the determination of lead absorption, was reported[3] in 1949 and the conclusions drawn at that time have since been supported by eight additional years' experience and approximately 60,000 specimens.

Blood-lead determinations are coming into more widespread use, with much benefit when all steps are carefully controlled. Figure 6 shows a specimen data sheet with detailed instructions for collecting the sample. Cards similar to those shown in Figures 4 and 5 can be set up for the blood-lead samples.

Biological specimens can give information of value in detecting exposure to other materials: namely, a number of heavy metals and several organics, including some of the common solvents. A few of the solvents, such as methanol, ethanol, and carbon disulfide, are found unchanged in blood and urine, while a number of materials produce significant quantities of characteristic metabolites. These measurable quantities can be found in the biological fluids in advance of permanent injury to the employees. The industrial hygiene department can then go into action to locate and control the source of the exposure.

E. SAFETY RECORDS

Safety and industrial hygiene services in the plant will inevitably overlap, and co-operation between the two is mutually beneficial. Four eyes see more than two, and the safety engineer frequently can call the hygienist's attention to conditions that he observes in his plant visits. No industrial hygiene survey is complete without a record of safety conditions observed in the course of the work, to be referred to the safety department for its consideration. Each department should be fully informed about the work of the other by exchange of reports and records. This exchange of reports also helps to promote a better understanding among persons working in these closely related fields of endeavor. Where this is not done there is too often a rivalry between these departments as to jurisdiction over certain phases of the work.

F. PERSONNEL RECORDS

Where the industrial hygiene service is a division of the medical department the personnel records pertinent to the work of this service are readily available. Where this is not the case or when special work, such as the control of a silica exposure, is being conducted, the personnel department can furnish the information on new employees essential for the interpretation of the results. At times a new employee may show silicotic nodulation in his chest x-ray, for example, that can be explained only by the personnel record of his previous employment history.

G. COMPENSATION CLAIM RECORDS

Compensation claim records are another key to industrial hygiene control; to be of greatest value they should be current and complete. Pertinent data

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[3] F. A. Patty, *Ind. Med. and Surg.*, **18**, 368 (1949).

DATE	NAME (Type or Print)	CLOCK	CHECK CORRECT OCCUPATION*							
			WORKS WITH SOLDER AS:					WORKS ON STEEL ONLY AS:		
			Torch Solderer	Filer	Booth Grinder	Repairman	Other (Specify)	Metal Finisher or Grinder	Assembler	Other (Specify)

*Obtain Accurate Information on Employee's Occupation and Classify Correctly.

Instructions for Collecting Blood Samples for the Determination of Lead

1. In collecting blood specimens every effort should be made to avoid contamination. It is not essential that the donor disrobe; however, caution should be exercised to see that the site of the puncture is free of lead.

2. Instructions in the proper use of vacutainer tubes and needles are attached hereto.

3. The needles provided have been sterilized prior to shipment.

4. Ten cubic centimeters or more of whole blood are desired for analysis. The capacity of the tube is approximately 20 cubic centimeters.

5. Coagulated blood does not interfere with the analysis, and it is preferred that *no* anticoagulant be added to the specimen.

6. After collection of specimen rinse the needle thoroughly, replace wire, and return unsterilized with blood specimen.

7. Attached hereto are copies of a form which, when completed, will give essential information regarding the occupation of the donor. The information provided in the column headed "Occupation" will be of value in correlating blood lead determinations with specific operations. It is requested that the completed form be returned with the specimen.

In the past there has been a lack of uniformity in the wording used for describing the occupation of the donor. In order to have a uniform nomenclature, we have listed the more typical occupations with a description of the work performed. Your cooperation in using these classifications will be appreciated.

Works with Solder as:

Torch solderer—Prepares base metal for solder by application of flux and tinning metal or applies solder to tinned surface.

Filer—Removes *solder* by using file. *Does not* use power tools.

Booth grinder—Works in solder grind booth. Uses power tools on solder.

Repairman—Uses file, disc or grinding wheel on solder. May apply solder before removing excess. Also repairs steel surfaces.

Other, such as *grinder* (similar to booth grinder except power tools are used on solder *outside* the booth), new hire, solder reclaim, booth cleaners, drip mold welders, blow-out, supervision, regrits wheels, etc.

Works on Steel Only as:

Metal finisher or grinder—Finishes steel surface only and does not remove solder.

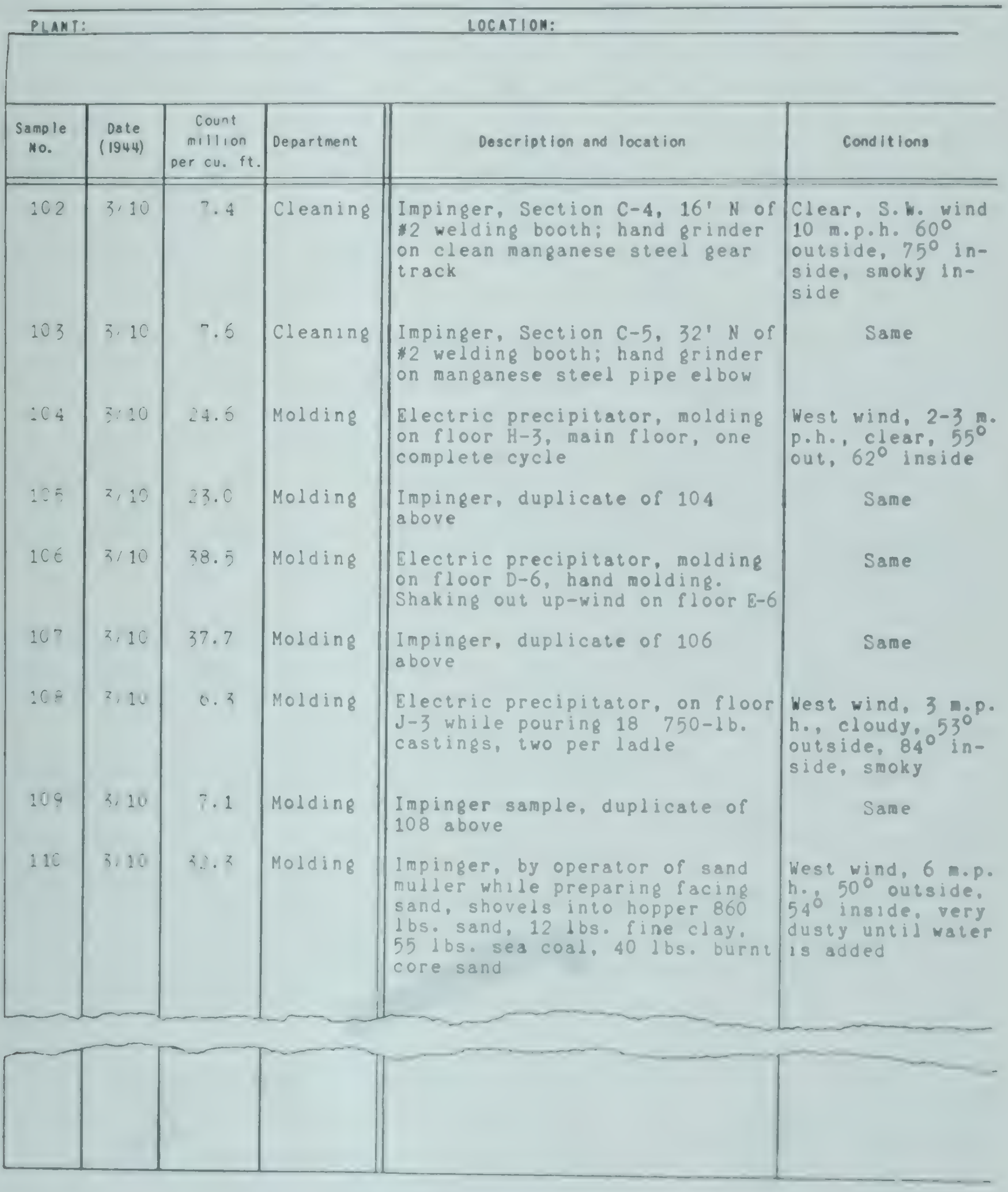
Assembler—This includes door hangers, door fitters, and other similar operations.

Other, such as clean and grind booth, stock handlers, supervision, etc.

8. The specimens and needles should be returned to the laboratory.

Figure 6. Specimen data sheet.

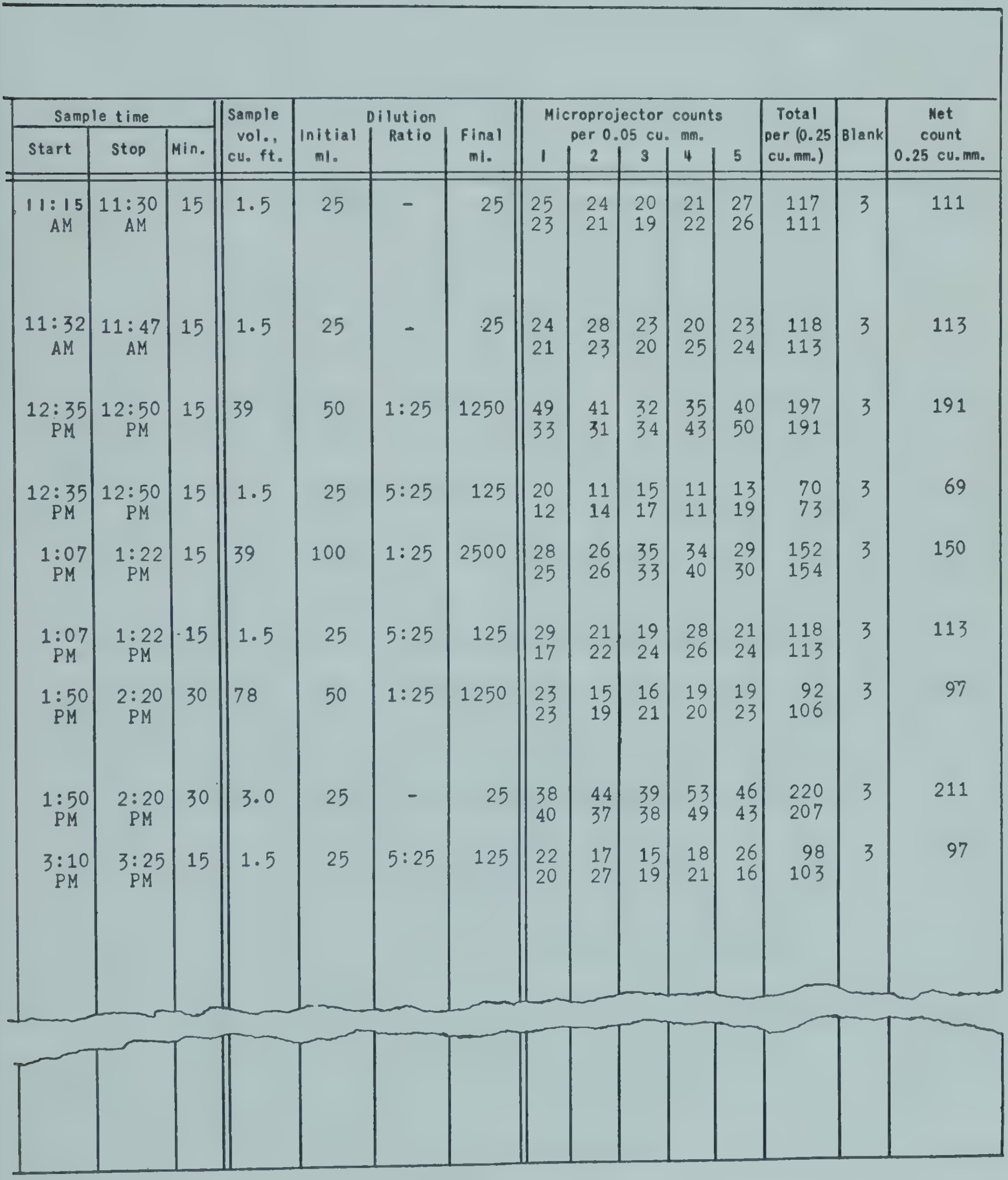
regarding the development of each case through to its final disposition, and including total cost, should be supplied the industrial hygiene laboratory. When these data are immediately available to the laboratory, whether company, insurance carrier, or state, technical investigations can be made while facts are fresh to determine the cause of the claim and the means of preventing similar occurrences. These records serve as a guide for trouble-shooting service and are an indicator of



PLANT: LOCATION:

Sample No.	Date (1944)	Count million per cu. ft.	Department	Description and location	Conditions
102	3/10	7.4	Cleaning	Impinger, Section C-4, 16' N of #2 welding booth; hand grinder on clean manganese steel gear track	Clear, S.W. wind 10 m.p.h. 60° outside, 75° inside, smoky inside
103	3/10	7.6	Cleaning	Impinger, Section C-5, 32' N of #2 welding booth; hand grinder on manganese steel pipe elbow	Same
104	3/10	24.6	Molding	Electric precipitator, molding on floor H-3, main floor, one complete cycle	West wind, 2-3 m.p.h., clear, 55° out, 62° inside
105	3/10	23.0	Molding	Impinger, duplicate of 104 above	Same
106	3/10	38.5	Molding	Electric precipitator, molding on floor D-6, hand molding. Shaking out up-wind on floor E-6	Same
107	3/10	37.7	Molding	Impinger, duplicate of 106 above	Same
108	3/10	6.3	Molding	Electric precipitator, on floor J-3 while pouring 18 750-lb. castings, two per ladle	West wind, 3 m.p.h., cloudy, 53° outside, 84° inside, smoky
109	3/10	7.1	Molding	Impinger sample, duplicate of 108 above	Same
110	3/10	32.3	Molding	Impinger, by operator of sand muller while preparing facing sand, shovels into hopper 860 lbs. sand, 12 lbs. fine clay, 55 lbs. sea coal, 40 lbs. burnt core sand	West wind, 6 m.p.h., 50° outside, 54° inside, very dusty until water is added

problems involved and results achieved. They show where additional control measures are needed, and should be filed under plant or department so that they may be reviewed by the industrial hygienist immediately before a visit to the plant. With tabulations of diseases, substances causing diseases, occupations, industries, years, and cost, they furnish valuable information. However, unless

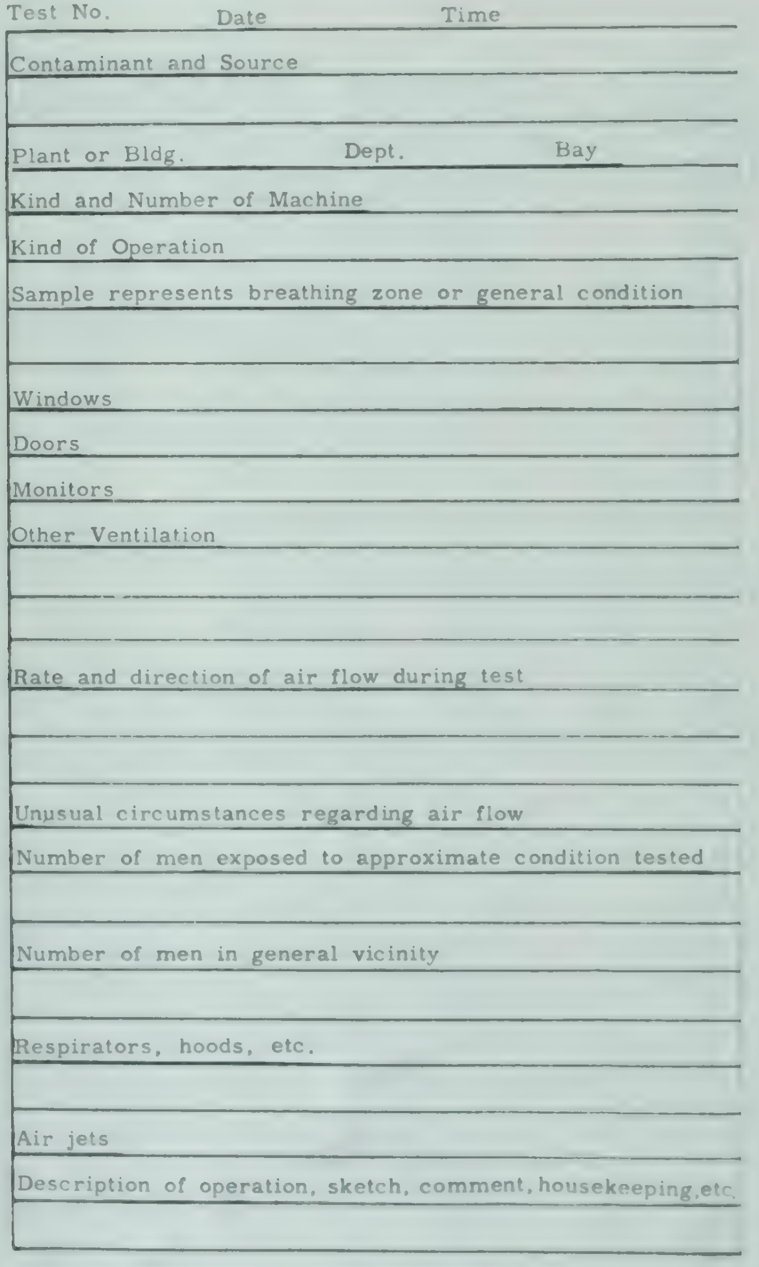


Sample time			Sample vol., cu. ft.	Dilution			Microprojector counts per 0.05 cu. mm.					Total per (0.25 cu.mm.)	Blank	Net count 0.25 cu.mm.
Start	Stop	Min.		Initial ml.	Ratio	Final ml.	1	2	3	4	5			
11:15 AM	11:30 AM	15	1.5	25	-	25	25 23	24 21	20 19	21 22	27 26	117 111	3	111
11:32 AM	11:47 AM	15	1.5	25	-	25	24 21	28 23	23 20	20 25	23 24	118 113	3	113
12:35 PM	12:50 PM	15	39	50	1:25	1250	49 33	41 31	32 34	35 43	40 50	197 191	3	191
12:35 PM	12:50 PM	15	1.5	25	5:25	125	20 12	11 14	15 17	11 11	13 19	70 73	3	69
1:07 PM	1:22 PM	15	39	100	1:25	2500	28 25	26 26	35 33	34 40	29 30	152 154	3	150
1:07 PM	1:22 PM	15	1.5	25	5:25	125	29 17	21 22	19 24	28 26	21 24	118 113	3	113
1:50 PM	2:20 PM	30	78	50	1:25	1250	23 23	15 19	16 21	19 20	19 23	92 106	3	97
1:50 PM	2:20 PM	30	3.0	25	-	25	38 40	44 37	39 38	53 49	46 43	220 207	3	211
3:10 PM	3:25 PM	15	1.5	25	5:25	125	22 20	17 27	15 19	18 21	26 16	98 103	3	97

competent men review and investigate these claims and assign correct diagnoses of disease and cause, the records are misleading and worse than useless.

III. Collection of Data about the Environment

The ordinary co-ordinate-ruled notebook makes the best primary record for industrial hygiene surveys. One book should be used for field notes and a second for laboratory records, which will also include a concise summary of the field notes. In the field book rough sketches and a brief description of the operation



Test No. Date Time

Contaminant and Source

Plant or Bldg. Dept. Bay

Kind and Number of Machine

Kind of Operation

Sample represents breathing zone or general condition

Windows

Doors

Monitors

Other Ventilation

Rate and direction of air flow during test

Unusual circumstances regarding air flow

Number of men exposed to approximate condition tested

Number of men in general vicinity

Respirators, hoods, etc.

Air jets

Description of operation, sketch, comment, housekeeping, etc.

Figure 7. Contaminant test sheet.

with data as to date, temperature, air movement, clock numbers of men exposed, sampling method, location of samples, sample time, and other pertinent observations may be entered. No additional ruling is needed. A half page or more should be devoted to each sample. For future reference it is very helpful to take a plant drawing and number the spaces between column lines in one direction and letter them in the other so that locations can be easily and definitely identified. The machine number, if available, also should be included among the data. For example, "swing frame grinder No. 147 in Section C-8 Cleaning Room" would locate a sample precisely.

The laboratory notebook should be ruled so that the field data, sample numbers, methods of handling the samples, and results are arranged for ready reference. Samples in each plant, or in larger plants in each department, are numbered consecutively. An example of such a notebook page for dust samples in a foundry survey is illustrated on pages 28 and 29.

PLANT DATE METER NO. ANALYZER NO. SHEET NO.

Column or Bay No.	Dept. No.	REMARKS	NETWORK			20 - 75	75 - 150	150 - 300	300 - 600	600 - 1200	1200 - 2400	2400 - 4800	4800 - 9600
			C	B	A								

DATA BY ____________________

Figure 8. Sound level record.

After sufficient data on a plant have been collected in this manner, the results for each department and operation may be tabulated in columns on a separate sheet so that average exposures over a year or more can be estimated, fluctuations observed, comparisons made, and so forth. Such year-to-year averages show the results of improvements and changes in operations.

When an industrial hygiene engineer is called upon to make many similar environmental surveys, it is often advisable to furnish him with an appropriate specific form to fill out at the time of sampling. One such form for air contaminants, reproduced in Figure 7, is punched for safe carrying and easy removal back at the laboratory.

In all cases the importance of drawing up correct special forms to be used by the investigator in the field can hardly be overemphasized. Upon the form itself may depend whether or not all needed information will be obtained, or whether a return trip may be required in important instances. Figure 8 shows a good form for recording sound-level values—determinations which are destined to become an increasingly important part of industrial hygiene.

Detailed and very inclusive plant survey forms employed by the United States Public Health Service, along with recommendations for their use, were given by Bloomfield[4] in 1945.

IV. Statistical Analysis of Data

A. FIRST INSPECTION

To the industrial hygienist who wishes to draw all the conclusions justified by the data he has collected—and none that are not justified—a certain working knowledge of the fundamentals of statistics is essential.[5]

The first and simplest calculation he will make is a total of the number of his items. Second, he will determine, by inspection, the item with the lowest value and the highest one. This gives him the *range* of his values. The logical question next occurring in regard to these data is: "Are they spread out more or less evenly throughout the range, or is there some tendency to group around a central value?" If the latter is true, "What is that central value?"

B. AVERAGES

There are a number of statistics that *measure the central tendency* of a *distribution*, which is the name given to an arrangement of numerical data. It is desirable to have some familiarity with five of them that are most commonly used and one or more of which will be the most valuable typical value in analyzing any given related data.

The *arithmetic mean*, which is commonly called the *average*, or simply *the mean*, is the best known and most often used. It should always be determined, for two reasons. First, nearly everyone is familiar with it and will understand its meaning. Second, it lends itself to mathematical calculations to determine other *parameters,* variables which characterize the series of data. The mean is determined by adding together all the values and dividing by the number of values.

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[4] J. J. Bloomfield, *Am. J. Pub. Health*, **35**, 559 (1945).

[5] This discussion aims to present fundamental definitions and techniques, and to point out pitfalls of statistics, in a simple, usable way, particularly for persons not mathematically trained who nevertheless find themselves with data to be used. For more complete coverage of statistics, standard texts should be consulted.

The second measure of central tendency in order of usage is the *median.* This value may give a better picture of the center of the data than the mean does and should always be considered. While it cannot be mathematically manipulated to determine other aspects of the series of data, it is deservedly appearing more often in the literature. The *median* is the middle value in an odd number of items arranged in order of magnitude, or the average of the two central values of an even number of items. Obviously, it is not affected by the range in the values nor by a few unusually high or low values. For this latter reason, particularly, it is very often more characteristic of the entire group than is the mean, which can be pulled either up or down by a few abnormally high or low values.

The third measure of central tendency that should be considered is the *mode.* The mode is less well known but simple to determine and often quite useful in an evaluation of data. The mode is the numerical value of most frequent occurrence. It may be identical with either the mean or the median and it may not. If it is not, then it should be reported as giving a useful picture of the arrangement of the data. There may be enough items on the opposite side of the median or mean to balance the modal value, but they may be spread out so that no one of them is as characteristic a value (occurs as often) as the mode. In the conclusions to be drawn, the action to follow, evaluation of any particular set of data, in such a case, knowledge of the existence and magnitude of the mode can prove valuable.

The fourth value of the central tendency of a group of data with which the industrial hygienist should have at least some familiarity is the *geometric mean.* He may not wish to calculate this value for his own data but he is sure to meet it in reading technical literature. The geometric mean is the *n*th root of the product of *n* items. This means that the logarithm of the geometric mean is equal to the average of the logarithms of the items. The geometric mean should be used as the measure of central tendency when the constant *rate* of change is desired, that is, if the quantities are constant percentages (which will plot as a straight line on logarithmic graph paper). In Figure 9, page 203, the geometric mean is the 50 per cent size as plotted on logarithmic probability paper.

A fifth type of average value is the *quadratic mean.* While the quadratic mean is not so often used as a measure of the central tendency of the original quantities themselves, it is the basis for the determination of a whole series of exceedingly valuable statistics known as *standard deviations.* The quadratic mean is the square root of the arithmetic mean of the squares of the items. The steps for computing it are (*1*) each item is squared; (*2*) all the squares are added; (*3*) the sum is divided by the number of items; and (*4*) the square root of the above mean of the squares is determined (cf. "The R.M.S. Sound Pressure," page 627).

C. DISPERSION

The average value (measured in one or more ways) may give the industrial hygienist the answer he wants from his data. However, before he can be sure that that is all he needs, it is advisable to examine the data in another way: that is, to determine what sort of variation of the items occurs around the average. The *range*, determined first, gives one answer. At the time of determining the median, when the individual items were arranged in order of magnitude, the *quartiles* and the *percentiles* could have been determined and would give more detailed answers. If a thorough analysis of the data is to be made, a frequency distribution should be drawn up. A *frequency distribution* is an arrangement of data in order of magnitude, with the frequency of occurrence of each value or each class interval of values (for example, Table 4, page 202). The quartiles divide the distribution into four parts: the first quartile marks the lower fourth; the median is the second quartile, marking half; and the third quartile marks the point of the lower three-fourths of the items in order of magnitude.

The *quartile deviation* (semi-interquartile range) is one half the distance between the first and third quartiles. In a normal distribution, the quartile deviation is identical with the *probable error*, which is much used in experimental work, for in each case the value is such that, when laid off above and below the average, 50 per cent of all individual values will be included. However, the term probable error should not be used to describe deviations occurring in a single frequency distribution but should be reserved for measurements of the unreliability of sampling.

In a very large number of items more minute analysis can be made by dividing them into percentiles, or 100 parts. For example, the ninetieth percentile value will show that only 10 per cent of the individual items were larger than this value.

Another method of measuring the scatter of the individual items is to determine the *average deviation* from either the mean or the median, whichever has been decided upon as the best measure of central tendency of the data. The average deviation is also called the *mean deviation*. As its name indicates, it is simply the average (arithmetic mean) of all the individual deviations, no account being taken as to whether the deviations are positive or negative. The average deviation is easily understood, is dependent upon the value of every item in the series, and is a minimum when figured from the median. In rare instances, it has been figured from the mode.

So far, measures for evaluation of the variation (scatter or dispersion) of data that are simple to compute and often very useful have been discussed. There is, however, another class of statistics, more complicated to determine, but much more valuable in many ways: *standard deviations*. A standard deviation is the quadratic mean (q.v. page 33) of all the individual deviations from the arithmetic mean. It appears in many if not most scientific analyses of data. Table 1 shows the per cent of items included within certain numbers of standard deviations from the mean of a normal distribution of items.

TABLE 1

Number of standard deviations (measured plus and minus from the mean)	Per cent of cases included
0.6745	50
1.000	68.26
2.000	95.46
3.000	99.73

The standard deviation is represented by the small Greek letter sigma, σ. It is considered to give the best description of the variability of a distribution, even though it is affected by every item in that distribution and so can be perhaps unduly influenced by a few extreme values. Especially in any analysis of research data, the standard deviation of the entire distribution, at least, should always be calculated. Other σ's, such as the σ of the mean, can be valuable, also, in showing how much credence to place in any given research data, but will not be dealt with here.

D. CORRELATION

Probably the simplest method of correlating two aspects of an industrial hygiene program is by means of a *dot diagram,* in which each value is inserted as a dot on graph paper, plotting one factor against another. The closer the "fit" of all dots to some type of mathematical curve, the greater the correlation (Cf. Figure 3, page 589). The important aspects of any *time series* in which fluctuations occur are likely to show easily and vividly when graphically presented. When a sufficiently large number of values for a variable have been determined it is often desirable to construct a *frequency diagram,* which is the graphical presentation of the frequency distribution (cf. Figure 8, page 202).

A simple and effective way to show the correlation between two different frequency distributions is in a correlation (or double-entry) table. Here each line and each column is in itself a frequency distribution.

For the calculation of the *coefficient of correlation,* which measures the *degree* of association between two variables, and is beyond the scope of this chapter, statistical texts should be consulted. Where the quantity and variability of data warrant it, the use of IBM cards and machines can be of great value in making possible more exhaustive analyses.

E. PRESENTATION OF DATA

Having carefully collected and properly analyzed his data, the hygienist is faced with the need of presenting it to someone. The most important point to remember here is: Does it show *readily* the real truth of the situation examined? If the truth is there, but hard to get at, busy managers and others who should see it will not have time to dig it out. If a casual inspection of the data, as presented, does not make the vital points stand out, very erroneous impressions may be gained. Therefore, with this in mind, the hygienist must decide the best method of presenting his data. This may be in summary only, but much is bound to be lacking so it is better to follow the summary of salient points with some more details.

Many times these can best be given in *tabular* form. Tables present all the data, grouped in whatever ways best bring out the truth. Much thought should go into the drawing up of the form for every table: what items are to appear in the column headings and what ones are to be listed down the left side. It may be that reversing or otherwise changing them will give a better picture to the reader.

A very excellent way to present many kinds of data is *graphic* presentation. Here, again, there is need to be absolutely sure the picture the observer gets is the correct one. For example, variation in the scales used for a graph can mean the difference between correct and incorrect interpretation by the reader. Visual impressions are very vivid and if a graph *looks* one way—contrary to the truth of the data—even though the numbers on it show otherwise, the erroneous visual image is apt to prevail. Such a graph is a very poor one—in fact, worse than useless. Unfortunately, many such have been published. One should always take a special look at his presentations to see if they are true representations.

One of the best forms of graph in many situations, probably the easiest to construct, and one that will be almost universally understood, is the *line drawing*. Whenever applicable, this is a good choice for the first graph constructed. *Bar diagrams* of several types are a second and reasonably well understood kind of graphs, which often present very vivid pictures of the data. Figure 9 shows a well-constructed bar diagram.[6] One can go from there through an extensive variety of types of graphs, each applicable to some particular situations and kinds of data. Every chart or graph is an instrument to make more vivid, and more quickly and easily understood, the data that must previously have existed in tabular form. If the graph becomes so cluttered or otherwise involved that it does not accomplish this, it should be revamped or abandoned entirely in favor of presentation of the table itself.

Another point to remember is that *every* table and *every* graph should be self-explanatory. Each should contain within itself, including all title and subscript material, *all* the information necessary to the complete understanding of the material presented. No one should ever have to search through accompanying text in order to understand exactly what a graph or a table means. The text can amplify and otherwise describe: it should never have to clarify the meaning of data presented in tables or graphs.

[6] *Injury Rates in New York State Industries, 1952*. New York State Dept. of Labor, Publication B-74, 1954.

It seems appropriate to mention here another excellent method available to the industrial hygienist for "graphic" presentation of his message. This is through the medium of photographs. Photographs tell stories with a minimum of explanations needed. "Before" and "after" pictures often can be particularly effective. As an adjunct to statistical and textual material, pictures should be used more often by industrial hygienists in their reports.

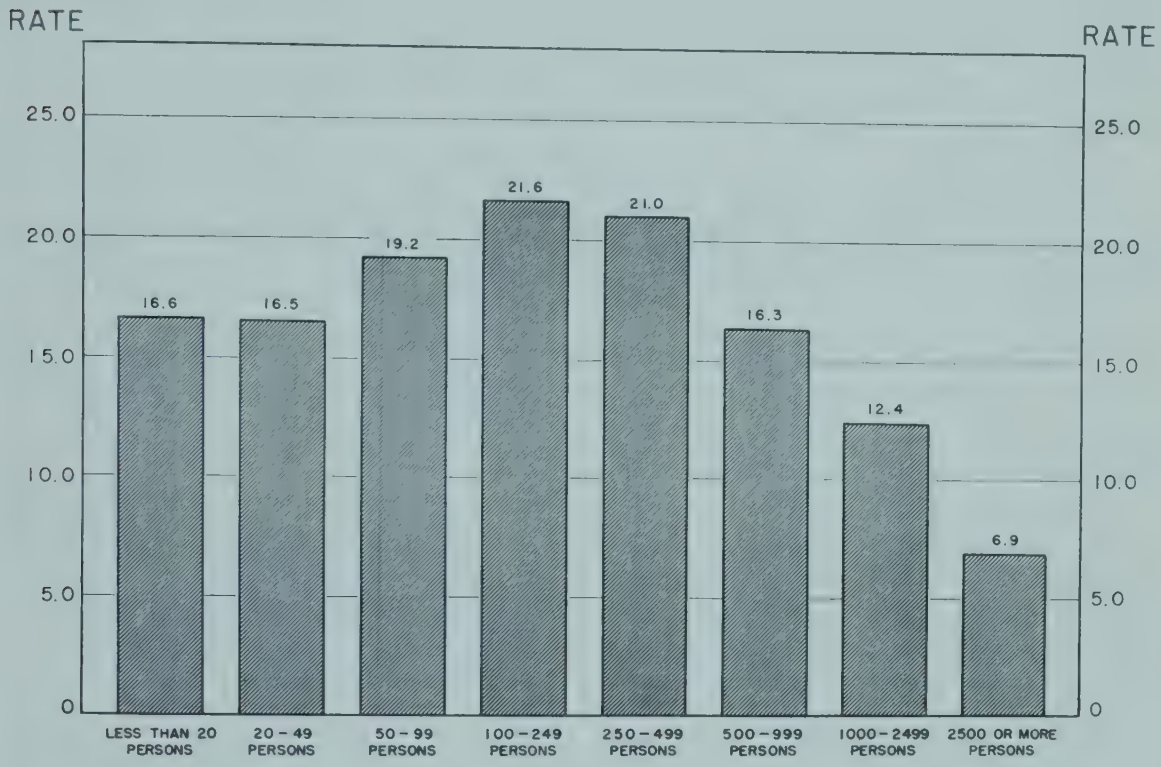

Figure 9. Injury-frequency rates (number of disabling injuries per million man-hours worked) in manufacturing industries, by size of reporting unit, New York State, 1952.

V. Industrial Hygiene Reports

The industrial hygiene survey report is the medium through which the results of the survey and the recommendations arising therefrom are transmitted to management. This report should include a brief description of the plant or department (unless it succeeds the first of a series on the same subject), the nature of the operations or any significant changes in operations since previous surveys, a discussion of control measures already in operation, tables listing the samples collected and results found, and an interpretation of these results in understandable terms. If available, the results of medical examinations or other findings on the individuals exposed should be correlated with the sample results. Finally, the report should include specific recommendations for control of the hazards found—an industrial hygiene report that includes only criticism of conditions without constructive recommendations is better retained in the hygienist's files. Space should be devoted to a brief summary of observations on housekeeping, on safety, and on employee reaction.

Before leaving the plant the hygienist should go over the report with the plant superintendent or department head. Such a discussion permits the inclusion in the final draft of operating objections to proposed changes and often develops ideas for correction that would not occur to the hygienist alone. It may also disclose any abnormality of operation at the time of the survey that may influence the sample results one way or another. Should it be necessary to await laboratory findings before preparing a rough draft, this draft should still be discussed with plant men.

The final draft of the industrial hygiene survey report should be addressed to the man in charge of operations, usually the works manager. Copies should be sent to the plant or department head, the chief engineer, the personnel director, the medical director, the safety engineer, and any other supervisor directly concerned.

The hygienist will accomplish more in the long run if his reports are not too broad. If he keeps in mind the long-range plan and then drives at one item at a time, he will be more easily understood and arrive at his objective sooner than if he proposes sweeping changes all at once.

An inclusive list of items to be looked for in the report of an inspection survey is given on page 42. A listing of statistics desirable in an investigation of dermatitis will be found on page 48. Suggested forms for reports of other special problems should be looked for in the discussion of the contaminant or physical stress involved.

VI. Research

No discussion of industrial hygiene records and reports would be complete without some mention of research. This activity will necessarily be confined to the larger organizations. In fact, in the past, a large part of it has come from national governmental agencies. More should be initiated by any industrial hygiene group in touch with any special problems not now well understood. Even a comparatively small organization may have at hand the means to develop answers needed elsewhere. These answers, when developed and published in the technical journals, can be collected and correlated with other research data by the larger strictly research organizations.

In particular, there is need for more complete records on: total exposure to ionizing radiation, exposure to heat above the comfort zone and below the presently recognized damage level, and, in fact, exposure concentrations and time for practically all air contaminants in order to more accurately fix hygienic standards. Correlation studies of hearing loss with exposure time and intensity levels of specific frequency bands of noise are needed. Possibly the most sorely needed data pertain to outdoor exposures or air-pollution studies relating contaminants to length of exposure and health. Here, unfortunately, methods for measuring air pollution and its effects, if any, on human beings have yet to be perfected—in some cases, developed.

VII. Conclusion

In conclusion, it may be stated that in no field of endeavor are good statistical data of more value than in industrial hygiene. There is no phase of it that does not require such tools, essential for evaluation and control. Several of the more important may be listed as follows:

1. Determining effects of atmospheric contaminants on people.
2. Planning action to be taken.
3. Appraising results of control measures.
4. Arousing interest of supervisory and management personnel.
5. Summarizing past experience, for example, in a plant, in an industry, or with a certain problem; this may well be by means of various forms of graphs.
6. Making comparison tables or graphs, such as between two methods of control, between two plants, or between two industries.
7. Showing trends by time series.
8. Developing proper standards for allowable concentrations of air contaminants.
9. Presenting problems and their solutions for employee education.
10. Confirming or refuting the validity of compensation claims.
11. Spotting unusually susceptible persons.

Always, back of the data stand the person who collected them and the one who analyzed them for conclusions to be drawn. An interesting historical example of the great value of an *inquiring mind* and *correlation of reports* occurred in the discovery of radium poisoning from dial painting (see page 722). The future will continue to present opportunities for those who exhibit such inquiring minds.

CHAPTER III

The Industrial Hygiene Survey and Personnel

FRANK A. PATTY

I. Introduction

Industrial hygiene surveys are personal investigations conducted within the premises of an industrial establishment, primarily to determine the nature and extent of any conditions that may adversely affect the well-being of the persons employed. Usually the first result of such a survey is the obtaining of information necessary to the development of engineering and medical control measures for avoiding or eliminating harmful situations.

Industrial hygiene preserves for employed adults their basic capital—health. It is a major problem of the industrial hygienist to maintain and safeguard the physical and mental capacities of workers, and to prolong their productive lives. This is a task of fundamental importance, for bodily impairment makes difficult the building and the maintaining of sound morale.

Ramazzini[1] is the first outstanding industrial hygienist of whom we have a considerable record. His investigations about 1700 A.D. into the causes of occupational diseases were remarkably enlightening. However, like many who came after him, he dwelled at some length upon therapeutic measures for the cure of such diseases and gave scant consideration to preventing them. Following this early auspicious beginning, it is remarkable that not until the third decade of the present century was there any widespread realization or acceptance of the next stage in the development of the industrial hygiene survey, that is, the utilizing of engineering methods of control for the actual prevention of disease. Even at such a recent date, industrial hygiene was largely on a complaint-investigation basis: when serious diseases developed, industrial hygiene investigations were undertaken to develop control measures for preventing a recurrence.

The design of the modern industrial hygiene survey is to recognize harmful exposures, and to bring them under control, before workmen experience injury or evidence any adverse signs or symptoms. This can be done by measuring exposures, evaluating their probable effects by existing toxicological and engineering standards, and utilizing sensitive biological examinations of exposed persons to discover the entrance of harmful materials into the human system in advance of injury. The qualified industrial hygienist recognizes his moral obligation to do his work well. This obligation precludes his accepting responsibilities beyond his capabilities; nor will he allow his findings to be influenced or colored by incompetent persons or selfish interests. The shrewd business man recognizes the value of keeping the industrial hygiene service on such a plane.

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[1] B. Ramazzini, *De morbis artificum diatriba,* 1700 and 1713.

II. Types of Surveys

In the practice of industrial hygiene there are four types of surveys: (*1*) the standardized inspection, which deals only with potentialities; (*2*) the preliminary or observational survey, which is a reconnaissance; (*3*) the investigational or appraisement survey, which has as its chief purpose the evaluation and control of existing harmful situations; and (*4*) the combined industrial hygiene and medical survey, which integrates the investigational survey with medical examinations of the workmen.

A. THE INSPECTION SURVEY

The inspection survey is conducted to establish whether or not an investigational survey is necessary. Wherever an investigation has been authorized, or its need established by occupational illness or otherwise, the inspection may be omitted. This survey consists of filling out blank forms or otherwise furnishing such data as the following: name and location of the plant; products manufactured or processed; number of male and female employees; their race; safety supervision; medical and first-aid services; the presence of sick-benefit organizations and availability of accident and sickness records; insurance, if any, for compensation and occupational diseases; the extent of industrial hygiene service available, and utilized, from all sources including the insurance carrier; the operations conducted and the number of employees engaged in each; raw materials, products, and recognized by-products; measures employed for dust, fume, and gas control; and methods of waste disposal.

This survey requires little or no technical training in industrial hygiene, and frequently is accomplished by filling in data supplied by the plant management and purchasing agent. Data thus collected can be evaluated for a single plant, or tabulated by industries for a city, community, state, or the country at large. When a large number of plants are involved, the data may be supplied from a representative group of 10 per cent or more, instead of from every industrial establishment concerned. A survey of this sort makes no pretense of being more than a rough indication of potential hazards, as obtained by visual observation or by interviews. It gives little or no insight into actual exposures to harmful materials, nor the suitability or effect of ventilation or other control measures. It is intended only as an indication of the scope of the industrial hygiene problem, and by this means plants are frequently selected for investigational surveys. One of the important aspects of the inspection survey is a routine check on materials purchased, a most essential factor in the prevention of harmful exposures.

B. THE PRELIMINARY INDUSTRIAL HYGIENE SURVEY

The preliminary or observational industrial hygiene survey is usually the immediate forerunner of a more extensive survey. It is made for the purpose of selecting locations in a plant where exposures or hazards are later to be evaluated by analytical studies in order to determine whether or not additional control is necessary. If no inspection survey has been made, the collection of pertinent data, such as previously mentioned, should now be included. The preliminary survey will also determine the apparatus necessary for the investigational survey. Depending upon the size and complexity of the operations, the time required for the preliminary survey may vary from a few minutes in a small shop to a day or more in large industrial plants. In the smaller plant the preliminary survey may immediately precede the final survey, and both may be accomplished in the same day by the same individual.

This preliminary survey is usually made with no equipment other than the five senses—or possibly six. It should be made by a man who is familiar with the type of industry involved, especially the chemistry of its products and by-products, and who is well grounded in the field of industrial hygiene. He may or may not be the man who is to make the final detailed survey, but he should be at least equally familiar with the problems involved in recognizing and evaluating exposures to harmful materials. The survey is best accomplished by following the industrial process through the plant from raw materials to finished products. The industrial hygienist should be accompanied by the production superintendent, or some other qualified plant man, to explain any process or steps in manufacture that are not evident to the surveyor. Among the men who are best suited to the role of guide for the investigator are the production superintendent, the plant engineer, the safety engineer, the plant chemist, and the foreman of the department under investigation. The plant physician or nurse may be able to point out departments that cause trouble. It hardly needs to be stated that a guide, to be of much help to the hygienist, must be prepared to supply or obtain information about any processes involved.

Since the surveyor ordinarily does not use equipment other than perhaps a smoke tube at this time, one of his most necessary assets is a well-developed and trained sense of smell. He should be able to recognize and identify all of the common gases and vapors that possess characteristic odors, tastes, or irritant effects, as well as to estimate roughly the concentrations of the majority of them. He should be alert to the personal appearance of the workers, and to any signs that may indicate adverse occupational exposures. This statement is not intended to suggest that nonmedical industrial hygienists should obviously examine the exposed portion of the workman's body for occupational marks or signs, or ask the workman to display such marks. He should not even allow it to be evident that he is making such observations, but at the same time there is abundant reason why he should keep alert to any indications that a workman may have been exposed to conditions sufficiently adverse to leave a mark or sign. In this way it may be possible to find a serious exposure that might otherwise be overlooked because of the intermittent or obscure nature of its causation. Chapter XV discusses at some length the visible signs of industrial diseases, and their possible significance, and points out as well many nonindustrial causes producing similar signs.

Frequently there are contributory operations, or intermittent operations, not in evidence at the time of the survey. These may include preliminary treatment of raw materials, disposal of by-products or waste products, and warehouse operations. The surveyor may learn of these through his experience in the industry, from a knowledge of similar operations, or by an extended discussion with a competent guide. He should always inquire into the location and method of conducting operations of such a nature, as well as into proposed new operations or pilot plant work, where such exist. A most important thing for the surveyor to remember is not to hurry, or be hurried, through a plant but to take sufficient time to give opportunity for recognition of the more obscure situations.

The preliminary survey should determine the presence or absence of control measures, and provide an opinion as to: *(1)* the probable need for, or effectiveness of, control; *(2)* the type of personnel as regards training, skill, or care; and *(3)* the attitude of management, supervising staff, and workmen toward health-control measures. At the end of the preliminary survey it may be desirable to give the management a report of findings and plans. Where an investigational survey is to be made without delay, it may not be necessary to discuss the situation with anyone other than the guide. In any case, having completed the preliminary survey, and decided where all investigations are to be made, the surveyor now selects the necessary equipment and undertakes the final survey.

C. THE INVESTIGATIONAL INDUSTRIAL HYGIENE SURVEY

1. Surveying the Plant

The investigational, or detailed, industrial hygiene survey involves the evaluation of all harmful exposures and the development of control measures. This is what is ordinarily referred to in the profession as an *industrial hygiene survey*. If no previous survey has been made of the plant, it is best to leave any equipment in a safe place and conduct a preliminary survey before undertaking the detailed investigation. It is frequently unnecessary to evaluate exposures by exact measurements. When control is the only objective, and it is obvious to the investigator that contaminants are excessive, he frequently can devise satisfactory control without the benefit of quantitative measurements.

However, when there is any question as to the necessity of control, or when facts for record are desired, samples of the atmosphere must be collected and evaluated. In surveys to determine the merits of a claim for compensation for injury allegedly arising from harmful exposure in industry, it is frequently necessary to obtain quantitative information about exposures in order to establish facts, rather than opinions, even though to the industrial hygienist the exposures may be obviously either insignificant or excessive. Records of periodic analyses of the extent of atmospheric contamination in any potentially harmful atmosphere are particularly valuable in evaluating claims presented for occupational diseases alleged to have developed over an extended period of time. In a potentially harmful situation, even though the investigator is completely satisfied that control is ample, sampling may be desirable for its psychological effect: it eliminates personal factors and gives the employees assurance of a safe environment.

The evaluation survey can well be accomplished with the co-operation of the production superintendent, the safety engineer, or the foremen of the particular departments in which investigations are to be made. If the results are to be representative, any air sampling or other quantitative measurements should be made during normal, as well as the most unfavorable, operating conditions and over a sufficient period of time to yield the complete exposure picture. The foremen can assist in maintaining these conditions; and precautions should be taken to avoid arousing the employees' curiosity, not only because of the false conditions created when workmen stop to watch or intentionally produce unnecessary air contamination, but also because it may precipitate ill will between employees and management if the impression is given that *harmful materials* may be present in the atmosphere. Since it is a practice in certain industries to pay a bonus for work in hazardous atmospheres where control of atmospheric contamination is difficult, industrial hygiene surveys there should be a matter of routine. If the plant has a physician or a nurse on duty, it is a good policy to visit him or her in order to establish cordial co-operation and to review any records of ill health. The plant physician may wish to accompany the hygienist during his survey of the plant, and this may prove advantageous to both, but it is an exceptional physician who can supply needed information about plant processes.

It is unpardonable conduct on the part of a surveyor to ask an employee suggestive question such as: Do you feel all right? Do you get sick often? Does breathing this atmosphere cause you any discomfort or irritation? The psychological effects of such questioning, which is only one step short of suggesting to a workman that he is ill, are obvious and undesirable. To some workmen the mere fact that tests for air-borne toxic materials are being made may indicate that dangerous conditions exist, and careless remarks of the investigator may grow to dire proportions and cause needless alarm among the workers. Although management often finds it advantageous to inform employees in advance of the purpose of an industrial hygiene survey, discussion with employees should be avoided by the industrial hygienist and left to the foremen or other representatives of management. Employees in many plants have learned to expect and appreciate the control measures that are the result of the industrial hygienist's work; trade unions have become aware of the benefits to the workmen to be derived from such investigations; while management especially values the savings in materials, men, and efficiency accruing from proper environmental control.

To the direct question "What are you doing?" or "What does that instrument do?" a disarming reply should be given. The industrial hygienist might say that he is making routine tests, determining ventilation requirements, studying the efficiency of the exhaust system, measuring solvent loss, or he may make some other similar statement of fact. Any remark about measuring the toxic vapors, seeing whether the air will make the workers ill, or seeing whether it is safe to work here would be an ill-considered, and possibly alarming, reply. It is not that the workman should be deceived but rather that he should not be alarmed about something that he probably would not fully understand. There have been instances where women painting dials with radioactive paints have been shunned in the cafeteria, and elsewhere, by other employees who feared they would contract "radium poisoning" by getting too close to them. "Dangerous half truths" are often potent forces in factory personnel relations, as elsewhere, and no industrial hygienist should contribute to their formation. There are, of course, exceptions to the rule against discussions with employees as well as to any other rule, but the fact remains that if industrial hygiene is to accomplish its purpose, a fair attitude must be maintained toward both factory management and the employees. Preservation of the employees' health is always the goal; facts must be reported to management; careless remarks that may instigate false rumors and alarms must be carefully avoided.

When a survey is made solely for the purpose of evaluating and controlling exposures, accuracy may be of secondary importance to speed. It may, therefore, be expedient to employ rapid field methods, even though their results may vary as much as plus or minus 20 per cent from the amount of contaminant actually present in the air. This is especially true of one-day surveys made in localities distant from the central laboratory. The reason for this is obvious since the survey cannot be concluded satisfactorily until the results are known. When the survey may extend over several days or longer, analytical methods requiring laboratory procedures are no serious handicap. In any case, methods and apparatus should never be used in the field by an investigator until he has found them satisfactory in his own use under controlled conditions.

The over-all exposure of an individual can sometimes be more accurately evaluated by analysis of a sample of his urine or blood than by a few samples of air. This is true of exposures to benzene (sulfate ratio), ketones, methanol, probably some of the chlorinated hydrocarbons, acrylonitrile, the fluorides, lead, and possibly other materials.

Air samples may be taken at one or several locations in order to determine individual exposures, general room-air conditions, and sources of contamination. Many variable factors must be considered at the time of sampling, in relation to normal, adverse, and optimal conditions. Single samples, though not to be scorned, should not be accepted as true indications of existing conditions because not only does the concentration of contaminants vary from minute to minute, day to day, and season to season, but also errors in sampling and analysis are certain to creep in occasionally even with experienced, and most careful, investigators. The more samples taken, the more evident will be the reasons for any variance in results, trends, peak concentrations, and other factors. There are arguments on each side of the question of the grab sample versus the extended-time sample; but, except for dusts, there can be no doubt that a large number of properly spaced grab samples tell a more comprehensive story than a single sample taken over the same period of time. Here again, the trained observer, from the senses of smell, taste, or feeling, may be able to evaluate an exposure accurately enough to establish either the necessity for its control or its insignificance. In large measure this depends upon previous observations of known amounts and similar magnitudes of the material to be evaluated, or so to speak, a calibration of individual sensitivity since there is some variation between persons in sense of smell.

All shifts should be observed—the night shift may create an exposure at some operation that the day shift conducts safely or vice versa. Air contaminants should be traced from their origin to the point or points of dispersion; air movements should be studied under normal and adverse conditions; and all unfavorable environmental factors should be evaluated. This evaluation should include temperature and humidity, drafts, illumination, noise, radiant energy, atmospheric dusts, fumes, vapors, fogs, mists, sprays, gases, as well as materials that cause skin afflictions, and any other factors that might adversely affect the health of the workman. It may even be necessary to control an excessive exposure before evaluation can be made of a coexisting minor exposure.

The wise industrial hygienist maintains a proper sense of values and is not unduly influenced by so-called "safe limits" and codes that may specify an eight-hour exposure figure and then ignore the time element. For instance, in the case of carbon monoxide, frequently limited by code or "safe limit" tables to 100 p.p.m., to take the attitude that the "permissible" amount should never be exceeded would be a gross error. More properly it should be considered as an average value, because brief exposures to moderately high concentrations of some contaminants that accumulate slowly are entirely acceptable. In a garage, for instance, the exhaust of a car being driven in or out may briefly raise the concentration to well over 500 p.p.m., but if the ventilation is sufficient to reduce this to below 100 p.p.m. within a few minutes, and the concentration does not average above 100 p.p.m., there is no harmful exposure. Scores of materials are in this category. Some of the more common ones are methanol and ethanol, glycols and their ethers, many esters, and, in fact, practically all of the materials that are highly soluble in water and neither narcotic, irritant, nor immediately toxic at the concentrations involved.

Evaluation and interpretation of findings may require consideration of some of the personal factors in competence and fatigue and the physical appearance of the workmen, as well as their age and sex. Posture at work is recognized as important for the normal individual and should be considered; for the physically handicapped individual it may become of much greater importance. Repeated motion requires special consideration of psychological and physical aptitude. Some industrial hygiene departments may find that sanitation in the restaurant and food trucks, the water supply, plumbing cross connections, and the plant sanitary facilities are within their range of responsibilities.

Dermatitis, when found to involve a significant number of employees, may require an epidemiological approach in order to evaluate causes or locate an obscure cause. The data collected for such a statistical study should include consideration of all factors that could possibly have any bearing upon the problem: number exposed, number affected, age, color, sex, complexion, personal cleanliness, opportunities for washing, occupation, department, materials contacted, parts of body affected, description of lesions, length of exposure, precautions observed, control measures used, and their result. A notation should be made of where the workmen eat lunch and smoke or loaf.

During the survey all raw materials, chemical solutions, and solvents warranting attention should be checked for chemical composition, methods of handling, storage, and disposal. Frequently it is desirable to take samples of plant materials to the laboratory for exhaustive chemical analysis in order to find harmful constituents. Although the industrial hygiene survey is primarily concerned with the physiological effects of air contaminants, fire and explosion hazards also should always be recognized. This precaution is desirable because the industrial hygienist is equipped to evaluate the technical problems involved; also, when a fire or explosion hazard can be shown, it may be easy to "sell" a coexistent need for a health-control program. The description of a vapor or dust contamination that may result in blowing up a section of a plant demands attention. Sound business will not permit procrastination on control when convinced that such a situation exists. This kind of response is not always elicited by moderate or borderline health problems. For detailed information on the recognition and control of fire and explosion hazards see Chapter XVI.

2. Developing Control of Harmful Situations

Having established the locations where additional control is necessary, the investigator should then devise the proper control methods, such as substitution, isolation, changes in operating technique or ventilation, and their specific application in the plant under study. This does not necessarily mean that where ventilation is the method of choice, he should forthwith compute the engineering data and lay out the details of a complicated ventilation system; but he should be prepared to give advice on the kind and proper application of an exhaust system, along with sufficient information upon basic requirements to enable the plant engineer to design, or obtain a design for, a satisfactory system. To be more specific, he should at least decide between general ventilation and exhaust at the source of contamination, the size, shape, and face velocity requirements of hoods, type of ventilating fan, the necessity of a dust collector, suitable types of dust collector, location of dust collector inside or outside, and the possibility of recirculation of the air. He should be able to understand and use the information in Chapters VIII, IX, and X. On occasion it may prove enormously advantageous to demonstrate by means of sheet metal, plywood, cardboard, or other easily fabricated material how the placing of baffles, or the proper shaping of a hood, can raise the efficiency of an existing exhaust system. The judicious use of a smoke tube, velometer, or other device to locate and measure air currents and cross drafts may give a clue to where a simple flange or baffle may be placed to direct properly the air flow surrounding a source of contamination, thereby converting a useless or ineffective exhaust system into an efficient one at little or no cost. The old box-type spray booths without baffles are fertile fields for improvement. The man who can go into a plant that has obsolete ventilating equipment not satisfactorily performing the function for which it was intended and, by directing maintenance and repair work or by placing a few improvised baffles, produce a readily noticeable improvement will probably have a better reception on his return visit than the fellow who insists upon a completely new and costly installation. This is not an unequivocal approval of the "make it last" doctrine that was forced upon most of us during wartime, but there are instances where this approach can be used very advantageously.

The extent to which the investigator may care to go in recommending and designing ventilation will depend largely upon the type of business he is surveying, his mechanical engineering experience and ability, and the policy of his organization. However, any industrial hygiene unit, to operate successfully in controlling industrial exposures, should include someone who is able to read and evaluate blueprints of proposed ventilating systems, advise upon their suitability, and offer suggestions for improvement.

When personal respiratory protection is needed, the nature and relative amount of contaminant against which protection is desired should be determined and specific recommendations made. A universal-type gas mask should not be recommended for an exposure where another type will give complete and longer protection at less cost. No canister gas mask should be recommended for routine use. Canister gas masks are emergency equipment only, and an untrained person attempting to wear such a gas mask for a prolonged period of work may collapse as a result of its high resistance to breathing.[2] All respiratory equipment should be examined for correct and properly placed canisters, filters, and so on, for properly functioning valves, for tightness of facepiece, and for leaks.

At the end of this investigational survey the hygienist is in possession of an accumulation of facts that must be correctly applied or else they become of academic interest only and serve little purpose in the promotion or control of health. The hygienist should develop control methods for all exposures and have them sufficiently crystallized to present to the plant management. Any unusual hazards found during the plant survey should be pointed out to and discussed with the physician or nurse, in order that by co-operation and knowledge of the complete picture both the industrial hygienist and the plant medical department may be aided in their work. The medical director is health officer for the plant, and, as such, it is important that he have knowledge of all information developed as a result of the survey.

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[2] L. Dautrebande, *Gaz de combat,* Univ. of Liége, Belgium, No. 1, 1935.

At the end of the survey, if not before, the plant manager or personnel director, the production superintendent, the safety engineer, and the maintenance engineer should be acquainted with all significant findings along with recommendations or suggestions for control. Objections may be raised, some of which can be overcome, whereas others may prove that alternates to some of the original proposals are more practical. It is obviously desirable that any major control program be explained and "sold" by the industrial hygienist to the man who pays for it, the man who supervises its installation, and the man responsible for unimpeded production; otherwise, misunderstandings and objections are almost certain to arise.

The alternative to "selling" the control program is the use of force. Unfortunately the use of force has been overworked and may have been a retarding influence in the promotion of industrial health. The words of a very famous American can well be applied here: "Speak softly and carry a big stick." There are, of course, instances where dangerous conditions exist and where the plant operators neglect or refuse to put through a satisfactory control program unless forced to do so, but these exceptions to the rule should not set the general pattern of relationship. The condition is certainly not improved if some untrained or uninformed representative of an official agency finds an unimportant exposure or potential exposure and, without proper evaluation of conditions, forthwith demands the installation of expensive and unnecessary control equipment. Too often, unnecessarily, his trip may have been followed up by a written order somewhat as follows: "Pursuant to an inspection of your premises you are hereby officially notified to provide exhaust ventilation that will be effective. . . . You are allowed 30 days in which to comply with this order." The informed plant manager who also has at his disposal qualified industrial hygiene service to evaluate properly his exposures and control needs is likely to avail himself of this assistance in order to point out any errors made in control recommendations; and future demands from the offending unit may be immediately met with strong opposition without proper consideration of their soundness. This practice of unnecessary force has not been confined to any group but has been found occasionally in all industrial hygiene groups, federal and state, departments of health and labor, government and insurance, military and civilian. The future course should be more toward the educational "selling" of sound control measures and curtailing the use of unnecessary force to get compliance with recommendations. Obviously, unsound recommendations should not be presented; and requests for control should be limited to those conditions investigated and weighed by competent, responsible investigators. The "big stick" will prove more effective if reserved for the class of management that fails to understand the necessity for and value of the control of harmful materials.

3. Records and Reports

There should, of course, always be a written confirmation report of the survey complete with findings and recommendations. This report may vary from a brief unbound typewritten one to a pretentious and voluminous manuscript, in an attractive and expensive binding, depending upon the nature of the relations between the surveyor and the surveyed and whether "dressing" is necessary, as well as upon the artistic temperament and literary ability of the surveyor. It is more likely to be read when brief, but should always be sufficiently detailed to establish the necessity for the recommendations presented along with it. Notes should have been made in a field notebook as a permanent record from which to develop the report; the practice of jotting down random bits of information on pieces of scratch paper that may be lost cannot be too strongly condemned. Details not recorded on the spot are often forgotten; and reports written from memory, though they may be sufficiently accurate in certain instances for control purposes, are almost certainly inadequate for legal record. Unless the original notes made on the job at the time of the survey can be produced, any record of atmospheric conditions in a plant offered as evidence in a court may be open to question.

It is important that the report of a survey reach the plant management while the situation is fresh in mind, never later than 30 days after the survey and preferably within two weeks. The value of the report is enhanced if it is delivered in person by the surveyor, or this result may be achieved by a personal call as soon as the management has read the report, in time to explain or support any findings or recommendations that may be questioned. Even though a recommendation was agreed upon at the time of the survey, if it arrives at an inopportune time, or tardily enough to have been forgotten or even for interest to have waned, management may assume an antagonistic attitude necessitating another personal contact. Reports or copies of reports should never be presented to other than plant management without the knowledge and permission of the management.

To have to depend upon presenting by mail only the recommendations developed from a survey, and omitting all information pointing to the necessity for each recommendation, is to work under a handicap that will materially lower the percentage of recommendations receiving compliance. To have the recommendations delivered in person, or followed up, by someone who is able neither to discuss them intelligently nor to defend them is worse than having no personal contact. Likewise, the more time that elapses between survey and report—beyond that necessary for preparation of the report—the lower will be the percentage of recommendations complied with.

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D. THE COMBINED INDUSTRIAL HYGIENE AND MEDICAL SURVEY

The combined industrial hygiene and medical survey is the most comprehensive of all industrial hygiene surveys and, depending upon the extent of the study, it usually requires from a few days to a few weeks or even months to complete. In addition to studies of environment and cursory observations of workmen as mentioned previously, this kind of investigation includes studies of individual workmen by medical technicians and physicians; it may include hematological, bacteriological, and parasitological studies as well as physical, x-ray, and other special medical examinations. The interpretation and evaluation of medical information belong in the field of medicine and require the services of physicians qualified by training in each of the above respective fields, or a physician who is closely associated with qualified men in each field upon whose knowledge he can draw. Likewise, engineering findings and recommendations should be handled by someone thoroughly familiar with the principles involved. The purpose of this combined survey may be to determine the exposure to atmospheric contaminants and any detectably adverse effects upon any of the exposed workmen that such contaminants may have caused; its major goal may be either evaluation or control. The scope may range from a single contaminant in a single plant up to a combination of contaminants throughout an industry. The study may evolve from the discovery of unexplained illness among workmen or from the known presence of contaminants in a workroom atmosphere that have, or are suspected of having, little-known or ill-defined, adverse effects.

Accepted maximum safe limits for atmospheric contaminants, notably those for benzene, carbon monoxide, lead, mercury, and silica-bearing dusts, have been set by comprehensive studies of this nature. Needless to say, any such standard "safe limit" is no more accurate than the method employed for air analysis and the concentration data recorded, regardless of how many qualified specialists evaluated the pathology found among workmen. For that reason, in all reports proposing safe working standards the methods of analysis should be explained and substantiated. Later and more dependable, or more sensitive, methods of analysis may throw more light upon the picture and show an accepted figure to be erroneous.

Combined industrial hygiene and medical surveys offer excellent opportunities for public-health research regarding adult health, at least the health of employed adults, and statistics for special groups are often more readily obtained in industry than from other sources. All special conditions obtaining in the industry studied must never be lost sight of, as they might have a bearing upon any general conclusions drawn from the statistics.

III. The Industrial Hygiene Unit

The industrial hygiene unit may vary from the simplest and least pretentious one-man unit to the most elaborate and inclusive unit, represented by the United

States Public Health Service, which in its Division of Industrial Hygiene at the National Institutes of Health[3] has included a staff of over 200 persons (see also pages 7–8). It is obvious that the small unit is limited in its scope and, therefore, if it is going to accomplish much toward the preservation of health in industry, it must necessarily exert its efforts mainly in preliminary and investigational surveys, with almost no time for pure research.

The National Institutes of Health, however, in 1943 had a *Research Section* that conducted laboratory research into numerous industrial hygiene problems, a *Dermatoses Investigations Section* to study the occurrence and prevention of occupational skin diseases, and a *States Relations Section*. Medical, engineering, and statistical units served as a source of supply of personnel to the sections: they recruited, trained, and assigned persons to sections for duty. Certain independent studies in the nature of services and research investigations also were carried on. As evidenced by the scope of the publications of this organization, industrial hygiene can be extended to influence practically all branches of community, adult health. All hygiene divisions are in a position to distribute educational information of great benefit in the promotion of industrial health.

State and city industrial hygiene units vary in the number of their personnel from over a score down to one or two men. They conduct research to a much smaller extent than the United States Public Health Service, and more recently have expended a considerable proportion of their time in conducting investigational surveys, although in their initial programs a large part of their efforts was spent on inspection surveys dealing with potentialities. The industrial expansion of 1942, 1943, and 1944 with the influx into many fields of relatively inexperienced management, as well as workmen, created an unprecedented demand for investigational surveys in order to minimize losses in man-hours due to ill health resulting from exposure to harmful materials.

There are several types of consultants and several organizations engaged in some form of industrial hygiene practice, ranging from those of an essentially statistical and educational nature to those devoted almost entirely to investigational surveys. The Industrial Hygiene Foundation may be mentioned as an organization having a general, educational, and investigational interest; whereas the industrial hygiene units of insurance companies are principally engaged in investigational surveys and individual control programs. While all industrial hygiene units in private industry have environmental evaluation and control as their primary objective, their activities vary considerably with the type and size of the industry and the viewpoint of management. In the larger and more progressive industries there is opportunity for a well-balanced and well-staffed unit with specialists in the different sciences represented, each having a chance to carry on research within his particular field.

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[3] J. J. Bloomfield, in W. N. Gafafer, ed., *Manual of Industrial Hygiene*. Saunders, Philadelphia, 1943.

IV. Qualifications and Training of Personnel

A. ADMINISTRATIVE INDUSTRIAL HYGIENIST

The necessary qualifications of a director of industrial hygiene have been previously described[4] and the educational qualifications of industrial hygienists discussed.[5] The qualifications here given for an industrial hygiene administrator represent a personal opinion guided by these previous descriptions, and modified by observation and experience.

The director of an industrial hygiene unit must have at least a bachelor's degree from a recognized school, and his basic education should be in science or medicine and should include chemistry, toxicology, and engineering. He should have at least five years' training in industrial hygiene with an official health organization, or a well-staffed and diversified industrial group, including experience in the evaluation and control of exposures to atmospheric contaminants. If he has an M.D. or a Ph.D. from a recognized school and his education included a good representation of such subjects as biochemistry, chemical engineering, mechanical engineering, ventilation, materia medica, pharmacology, physiology, and toxicology, the experience requirement may be reduced to three years.

He should be able to understand and discuss all phases of industrial hygiene and toxicology and be interested in public health and industrial relations. He should be able to set up systems for keeping records of results achieved and for planning future activities. He should be an avid reader and should devise a systematic bibliography of references covering the field of his interests and activities. He should be able to locate the cause of cases of industrial ill health presented by a physician, to make comprehensive analyses of health conditions in industries, to draw adequate conclusions, and to prepare clear and informative reports for publication. He must have tact, courage of his convictions, and good judgment and must be able to address a group. He must do sufficient field work to keep the viewpoint of the man in the field, and it is necessary that he maintain a wide, personal acquaintance with the men active in promoting industrial health. He should support and attend public meetings where current problems in the field are discussed.

B. INDUSTRIAL HYGIENIST

An industrial hygienist should be able to determine the necessity of making specific studies of industrial conditions; to conduct or supervise surveys; to recognize and evaluate harmful conditions; to develop control measures for all adverse situations; to prepare comprehensive reports of findings, with control recommendations; and to present verbally to management, to plant physicians, and to maintenance, production, and safety engineers the necessity and value of control measures.

He should have at least a bachelor's degree from a recognized school, or equivalent training and experience. It is desirable that his basic education and training should include chemistry, toxicology, mechanical engineering, and the principles of illumination, ventilation, and air conditioning. He should be interested in public health and have at least one year's study in a school of industrial hygiene, or a year of supervised training with a unit of industrial hygiene that included field surveys.

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[4] R. R. Sayers and J. J. Bloomfield, *Am. J. Pub. Health*, **26**, 1087 (1936).

[5] C. D. Selby, H. F. Vaughan, L. D. Bristol, P. Drinker, T. L. Hatch, and P. A. Neal, *Am. J. Pub. Health* **31**, 728 (1941).

C. OTHER PERSONNEL

The other persons who may be found in the well-staffed units include specialists whose chief qualifications or interests are in some particular part of the field, such as the industrial toxicologist, industrial hygiene physician, industrial hygiene engineer, industrial hygiene chemist, ventilation engineer, analytical chemist, statistician, nurse, technicians, and stenographers. The qualifications and interests of the persons comprising this personnel necessarily will vary widely. While on the one hand the interests of some may cover the entire field, the interests of others may be very specific. As an example, a man with the basic education of a mechanical engineer may be classified as a ventilation engineer, an industrial hygiene engineer, or an industrial hygienist, depending upon the scope of his activities and interests in the field of industrial health. The same applies to the physician, the chemist, the toxicologist, the physicist, and possibly others. Each may start as a specialist and by association, experience, and study develop interest in and knowledge of the entire field, in which case he may properly lay claim to the title of *industrial hygienist;* if he wishes to retain identity with his earlier and basic profession, he may then use that term as a prefix and call himself engineer, physician, or chemist industrial hygienist.

The term "industrial hygiene engineer" has been used freely and loosely in the past to apply to every individual, not holding a degree in medicine, who aligned himself with, or, in some instances, expressed a desire to align with some industrial hygiene unit. It made little difference whether the individual had ever studied or been associated with any engineering activities so long as he could make some kind of evaluation of atmospheric contamination. Such a man can more properly be called a technician or scientific aide. Unsuccessful attempts have been made to impose the term "sanitarian" upon persons engaged in industrial hygiene work. The connotation of the word suggests dealings with the water supply, sewage, and waste disposal. Although this may be an important part of industrial hygiene, it is not all of it, and therefore the term is not appropriately inclusive and could properly apply only to a specialist in the field, industrial hygiene sanitarian.

The term "etiologist" has been suggested as being more specific and meaningful than "industrial hygienist," but this word applies only to the investigation into causes of disease and carries no implication of ability to devise and apply correct control measures. Since the industrial hygiene survey report that does not include suggestions or recommendations for the control of any unhealthful conditions found has a disappointingly flat flavor, the *industrial hygienist* must be more than an etiologist.

CHAPTER IV

Human Engineering and Industrial Safety*

ROSS A. McFARLAND

I. Introduction

A. THE ROLE OF HUMAN ENGINEERING IN ACCIDENT PREVENTION

In this country, the loss of life and the incapacity resulting from accidents are as great as, or greater than, loss and incapacity from any known disease entity. Accidental injury ranks first as the leading cause of death for persons between 1 and 34 years of age, and second for those between 35 and 44. The fact that many of these victims are in the younger productive age groups, in contrast to those whose deaths are attributable to certain degenerative diseases, implies an enormous cost to the industrial resources of the country in terms of "life-years." Measurement of nothing but the fact that a death has occurred is less meaningful than the measurement of how much "life-time" has been lost prematurely. An 80-year-old man dying of heart disease in retirement and a 25-year-old worker killed on the job are each counted as one death under present methods.[1]

It has often been stated that the majority of industrial accidents can be attributed to human error. This is true not only in the various fields of transportation, but also in most other industries that have not been completely mechanized. Many believe, therefore, that the greatest promise in the control of accidents lies in the elimination of the human element by complete mechanization. Although this has been accomplished in some fields, the fact remains that a large percentage of the persons who are gainfully employed operate, or are exposed to, some type of equipment or machinery.

Some industrial operations may be classified as skilled, but the majority are semiskilled or unskilled in nature. It is necessary, therefore, to think of men working at machines of all types: trucks, tractors, trains, derricks, cranes, lathes, punch presses, mixers, and so forth. Their jobs may vary from working in steel mills and chemical plants to constructing and demolishing buildings, working on poles, building cross-country pipelines or highways. In some cases, the workers may be exposed to extremes of noise and vibration or to marked variations in temperature and humidity, or to harmful dusts, fumes, and gases. Human error or failure may occur in many of these situations, and environmental conditions or operating practices may predispose the workers to accidents.[2]

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* This study was sponsored by the Commission on Accidental Trauma of the Armed Forces Epidemiological Board, Department of Defense, and supported by funds from the Research and Development Division, Office of the Surgeon General, Department of the Army.

[1] R. A. McFarland, Human engineering aspects of safety, *Mech. Eng.*, **76**, No. 5, 407–410 (1954).

In addition to the established methods of combating industrial accidents, such as safety-education programs and special safety equipment, there is a relatively new discipline, commonly called human engineering, which can reduce accidents by relating the mechanical design of the equipment to the biological and psychological characteristics of the operator. It seems reasonable to require that machines be designed from the man outward, with the instruments and controls considered as extensions of his nervous system and body appendages. This implies that machines and working areas must be built around the operators rather than placing the workers in a setting without due regard for their requirements and capacities. Unless machines are so constructed, it is hardly fair to attribute so many accidents to human failure, as is usually done.

If this point of view is carried out in practice, fewer accidents should result, training costs should be reduced, and the necessity for extensive redesign of equipment after it is put into use should be eliminated. This principle holds true whether an employee is operating motorized equipment on the highway, flying an aeroplane, operating a lathe or punch press, or carrying out any of the numerous mechanized duties of a manufacturing plant.[3]

1. *Designing for Human Capabilities and Limitations*

Although it was pointed out first almost 50 years ago that the design of tools should take into account the variations in the physiques of different workers, relatively little has been done since along these lines.[4] By and large, the employee today must still adapt himself to the tools and equipment provided him and to the methods of work prescribed for everyone. However, the gains that result from adapting the equipment and working methods to the individual are of demonstrated significance. This does not mean, as is sometimes believed, that equipment and methods need to be developed for each individual, but rather that optimum conditions can be discovered for groups of workers. Thus, the best arrangements can be set forth with reference to human capabilities.

Machine speeds during certain industrial operations, for example, are sometimes clearly un-co-ordinated with the capacities of the operators. With slow speeds the worker may become impatient, while fast speeds may disturb him because of his inability to keep up. In either case accidents may result. As the speed of work increases beyond a point, a disproportionately greater increase in

[2] R. A. McFarland, Chairman, Proceedings of the President's Conference on Industrial Safety, March 23, 24, and 25, 1949, *Bull.* No. **112**, Bur. Labor Standards, U. S. Dept. of Labor, 1949.

[3] R. A. McFarland, Human engineering: a new approach to driver efficiency and transport safety, *Soc. Automotive Engrs. Trans.*, **62**, 335–345 (1954).

[4] F. W. Taylor, *The Principles of Scientific Management*, Harper, New York, 1911

errors (and therefore, presumably, of accidents) has been observed. This may be especially true for older workers.

It is recognized also that as work becomes more physically demanding a greater number of accidents may be expected. The importance of severity of work as a factor in safety is frequently underestimated. Ordinarily, with more strenuous operations the speed of work falls off considerably toward the end of the working day. Thus, in many instances the opportunity for accidents is also reduced, and when the safety of jobs is compared in terms of the number of accidents incurred, differences may be obscured or minimized. If the accident rate is taken in terms of the number of accidents incurred per unit of work completed, quite a different picture may emerge. In one case, for example, while the rate of accidents increased only 50 per cent from the beginning to the end of the working day in a less demanding factory job, it increased 275 per cent for a more demanding job.[5] In such a situation the need for consideration of ways and means for reducing physical demands, such as through increased leverage and booster systems, is obvious.

One of the most important concepts of human engineering is thus the design of equipment in terms of human capabilities and limitations. We have learned that difficulties arise when mechanization becomes too complicated for human operators. Therefore, everything must be done to design the equipment and to set up the operating procedures to facilitate the greatest possible efficiency and safety. More precisely stated, first, the engineer must have an understanding of the sense organs and the characteristics of human perception if satisfactory information is to be supplied from sounds and lights in the operation of equipment. In general, man is a poor monitor of equipment. Second, the engineer must not place unreasonable demands upon the operator in regard to the physical responses involved, for example, in reaching or operating a control or lever or in clearly differentiating between two or more controls. Otherwise, an inadvertent operation of a switch or control may occur. Third, the engineer must consider that the operator of equipment is frequently suffering from temporary impairment of functions, such as fatigue, thus causing inefficiency, and that there may be changes in function as a result of aging. Finally, the physiological and environmental conditions such as temperature, humidity, toxic gases, and other factors must be considered, or physiological limits may be exceeded.[1]

B. PRINCIPLES OF ADVANCE ANALYSIS

The initial phase of any human engineering program in industry should consist, wherever possible, of an advance analysis of all possible faults in equipment and working areas. If defects are present, it is only a matter of time before some operator fails and has an accident. Advance analysis assumes an operational job analysis that should include a survey of the nature of the task, the work surroundings, the location of controls and instruments, and the way the operator performs his duties. A functional concept of accidents should be maintained throughout—that is, the errors that may occur while the operator is working at the machine should be anticipated. The repetition or recurrence of near or real accidents clearly indicates a need for redesigning. Another consideration relates to human limitations. It should be assumed that no worker is a perfect one. In fact, he may be far below the ability assumed by the designer. If his duties are too complex, the cumulative burden is great and he may reach or exceed his limits of attention and ability. Finally, a wide margin of safety should be provided to eliminate any possible situation that places the operator near his maximum ability with regard to aptitude or effort, especially when adverse factors are present.[6]

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[5] J. Goldmark, M. D. Hopkins, and P. S. Florence. A comparison of an eight-hour plant and a ten-hour plant, *Pub. Health Bull.* No. **106,** 1920.

1. Operational Job Analysis

No engineer would accept an assignment to design a motor unless he was also provided with information as to what the motor was for, the conditions under which it would operate, and the type of load it was expected to handle. In other words, specifications are required and these rest upon an analysis of the job the motor is to perform. If we view an employee as an intricate industrial machine, then before he is assigned to a given task, the work should be analyzed in terms of demands to be placed on this human machine. No engineer would design a motor to operate under conditions of extreme cold without considering the possible damage that might result from this operating condition and providing the necessary safeguards, such as proper tolerances, lubricants, and the like. Surely, the human machine should receive as much consideration as a motor. The potentialities of job analysis for the prevention of industrial accidents are very great, but thus far they have been only partially exploited and developed.

Job analysis can be divided into three broad areas: the surround, the machine, and the operator. The surround refers to the operational area within which the operator is required to perform. For example, poorly lighted areas or passages are one of the conditions among which the operator must sometimes perform his work. The second area is the machine. Job analysis can be applied to equipment design with resulting improvement in operator safety and corresponding reduction in industrial accidents. The third area, which deals specifically with the selection and placement of personnel, is generally not included in human engineering.

The hazardous features and conditions of some jobs are evident upon casual inspection. No special professional skill is required to determine that a power-driven ripsaw is potentially dangerous to the hands of the operator. The services of a safety engineer are not required to reach the conclusion that the operator may come in contact with the blade. His services become valuable, however, in deciding what kind of a safety device should be employed and just how it should be designed and used. Common sense and unaided observation can, in some instances, be adequate to identify the potential dangers of a job.

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[6] R. A. McFarland, *Human Factors in Air Transport Design*, McGraw-Hill, New York, 1946.

The dangerous aspects of other jobs can be identified by knowing some of the technical features of the equipment. For example, the danger inherent in some hydroelectric generators when there is a sudden loss of load can be deduced from characteristics of the generator, the turbines, and the controlling valves.

Direct observational and logical procedures can often utilize some of the special techniques that have been developed as aids in locating the danger spots in a job. Such aids as motion-picture photography, interviews with experienced operators, and analysis of control movements and forces become especially useful for jobs that are intricate, those that are part of a more complicated system of men and equipment, and those in which failures and accidents rarely occur. Each of these methods is a tool useful in abstracting from an operator's performance those items that involve danger to the operator, his fellow workmen, or the installation and its personnel.

In such studies, the concept of an error rather than an accident is often preferable because of the additional latitude in the connotation of the term "error." Since corrective action can be taken by the detection of "near accidents," attention is given to both potential and real accidents. A search for errors in performance may uncover near accidents or events that would result in catastrophe under special circumstances. Indeed, many accidents can result only when more than one error is made. In some systems, one may make an error and the mistake will be compensated for by another operator or by some characteristic of the machinery. Serious trouble may develop only when more than one error is made somewhere in the system within a limited period of time. Thus, some errors can be thought of as sufficient conditions for an accident, whereas other errors are necessary, but not sufficient, conditions for an accident. A program for reducing accidents must consider both kinds.

Even when attention is directed to errors so as to include instances in which serious trouble might have developed but did not, an observer might spend many hours watching a competent operator without finding enough cases to permit proper study and evaluation. Accordingly, special techniques are needed to accentuate the error aspect of the performance either by experimentally increasing the frequency of errors or by telescoping time so that an adequate sample of errors is available for study. Some of the typical methods used in this kind of job analysis will now be examined.[2]

a. Time and Motion Study. Time and motion study has made little direct contribution to problems in safety. To a considerable extent this can be attributed to a misunderstanding of the nature and purpose of this type of analysis. Time and motion study is simply a means for obtaining a description of current methods of work. It is when the findings from the time and motion study are used as a basis for setting up new and presumably improved methods of work that disagreement comes.

First of all, the time and motion study analyst is handicapped because the results of his efforts are ordinarily gauged solely on the basis of increases in production. While he will not knowingly substitute a less safe motion for a more safe one, he nonetheless must devote his efforts toward increasing production, since that is his assigned task. The limited scope of activities forced upon him implies that full advantage is not being taken of his special training. Second, economy procedures are frequently confused with the "speed-up." While it is the purpose of time and motion economy to increase the amount of production, it is not the intent to do so simply by increasing the speed of the motions presently employed. Basically, time and motion economy seeks to eliminate slow movements and those that accomplish little work, and to substitute motions that are naturally more rapid and those that accomplish more work. Thus, while the speed at which items of work are completed is increased, this increase is not to be achieved through greater costs to the employee. Unfortunately, the principles of time and motion economy have not been developed with safety in mind, and, as a consequence, it cannot be said that the employment of this technique will *necessarily* result in a decrease in accidents.[2]

b. Analysis of Errors and Near Accidents. The job description itself may or may not indicate which types of activities are likely to lead to accidents. In some instances, unsafe acts are very obvious. Thus, following closely behind a vehicle while traveling at high speeds is clearly dangerous. In other cases, the danger might not be so obvious. The mangle, which requires the operator to support herself on one leg while operating a foot pedal with the other, would seem to have some elements of danger, yet one cannot be absolutely certain. Finally, some types of activities may be quite dangerous and yet go unsuspected. In certain situations, the application of the accepted principle in time and motion economy of opposite and symmetrical motions of both arms may be poor because it does not permit the simultaneous lateral movements to be well guarded by the eyes.

As a consequence, some attempts have been made to analyze case reports of accidents in order to determine mistakes made by the worker which led to the event.[7] The range of possible mistakes that an individual can make is great and the opportunity varies markedly from one occupation to another.[8] This means that there is little possibility of generalizing the findings with respect to unsafe acts from one occupation to another. Furthermore, if unsafe acts are described in very general terms, as in the American Standard Code for Compiling Accident Causes, important details will be lost. While it is of some help in the construction industry to know that a significant number of accidents are due to poor or faulty use of tools, it would be of immeasurably greater help to know that more accidents result when fixed or controlled movements are used in swinging a pick than when ballistic movements are used. The value of an analysis of errors and unsafe acts will be in direct proportion to the specificity with which the error or act is described. As an aid in a preliminary analysis of unsafe acts in accident reports, and for the purposes of occupational and industrial comparisons, some system like the American Standard Code will be helpful.

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[7] E. E. Ghiselli and C. W. Brown, *Personnel and Industrial Psychology*, McGraw-Hill New York, 1948.

[8] R. P. Blake, ed., *Industrial Safety*. Prentice-Hall, New York, 1946.

The study of near accidents is a part of the critical incident technique, described by Flanagan. In this approach, incidents having a special significance or relevance to accidents are recorded with the aim of permitting inferences and predictions to be made about the person performing the act. Such data can assist in the advance elimination of the accident-repeating individual, just as analyses of near accidents can assist in the elimination of the accident-inducing situation or work method.[9]

II. Equipment Design in Relation to Human Body Size

Whenever the design engineer is concerned with the development of machinery to be operated by man, he must make decisions as to the dimensions and arrangements of the operator's control area and all of its components. In some instances, he is given general directions such as "all machine controls must be conveniently accessible"; or he is instructed to avoid arrangements that involve "reaching with hand, foot, or tool beyond range of clear vision," "off balance positions," "inadequate head room," "inadequate clearances," and "inadequate working space about machines or equipment."[10] He is rarely supplied with the detailed quantitative descriptions of man that will enable him to meet these specifications. The design engineer, then, has been obliged to work out required dimensions on the basis of general familiarity and experience with the operation, "educated guesses," measurements of trials with only a few subjects, and reference to previous design (which, in all likelihood, was established upon an equally tenuous basis). It is probable that in the great majority of cases where design deficiencies in fitting the machine to the man have occurred, the errors have resulted not from lack of concern for the operator but rather from the lack of adequate descriptions of his body measurements and other physical and physiological characteristics upon which equipment design must be based. Such a situation is clearly unacceptable from the point of view of industrial safety, since the extent and the success of the provisions that are made for the satisfaction of human requirements in any design or work situation will determine, to a considerable degree, both the safety and the over-all efficiency of the operating personnel.[2]

It is obvious, then, that designers must have access to descriptive data on the body size of the populations who are to use their machines. These data can be obtained with the aid of the metrical and statistical techniques of anthropometry, a branch of physical anthropology dealing with the measurement of man.

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[9] J. C. Flanagan, The critical incident technique in the study of individuals. *Modern Educational Problems, Report of the 17th Educational Conference.* American Council on Education, Washington, 1952.

[10] Safety subjects, *Bull.* No. 67, Bur. Labor Standards, U. S. Dept. of Labor. 1944.

It is suggested that the engineer consult with the anthropologist during the initial design stages rather than at a later period when modifications may be costly. Although handbooks of biological data are of value as general reference and orientation material for the industrial specialist, the technical background and experience of the anthropologist are desirable for the most efficient gathering, interpretation, and application of the data.

When the design engineer works in collaboration with the anthropologist he should be sure that the anthropologist *(1)* is adequately instructed as to the role of the man in the specific industrial operation; *(2)* knows the composition of the group of future operators in terms of age, sex, and any requirements used in personnel selection; *(3)* is aware of the body position(s) for operation of the equipment; and *(4)* is present to interpret and assist in the application of his data when the plans are being drawn.[2]

In some cases it may not be feasible or possible to design new machines "from the man out"; instead, the anthropologist may be forced to evaluate existing models. On such occasions the suggested procedure is as follows: he should, *first*, describe his population; *second*, ascertain the proportion of that population accommodated and the quality of that accommodation, with respect to comfort, efficiency, health, and safety; and, *third*, if not all operators are accommodated, establish size limits for selection and training. It seems obvious that a man should not be given intensive instruction only to find that he cannot fit the machine for which he has been trained; but such instances have occurred. In such a case the anthropologist must, *fourth*, then ascertain the nature and cause of any difficulties encountered and attempt to remedy them. His chief interest will inevitably be in specific installations within the working area, since these are usually responsible for many operational difficulties. After these first four steps have been taken, the experience gained in such evaluations should be used to set up criteria for new designs.[11]

A. THE APPLICATION OF ANTHROPOMETRIC DATA

1. *Traditional Anthropometric Measurements*

Anthropometric measurements were originally devised to facilitate the study of evolution and race and hence some of the available data are of little use to the design engineer. In general, however, many of the traditional anthropometric dimensions are of some utility in problems of space design. For the most part they consist of body lengths, breadths, depths, and circumferences as illustrated in Figure. 1. These static dimensions, as they may be called, are useful in determining clearances and allowances in the working area. Examples would be the minimum width of a chair as based on seat breadth, or minimum head clearance as based on sitting height or stature. In some cases new static measurements must be devised to fit special situations that arise only in space-design problems, such as the distance from the floor to the under side of thigh (popliteal height), when seated, in order to assure a comfortable seat height. For uniformity and accuracy all anthropometric measurements should be taken either by anthropologists or by those adequately trained in the techniques of anthropometry. Past experience has shown that human body dimensions taken during the course of routine military physical examinations, for example, can rarely be accepted at face value.

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[11] R. A. McFarland, A. Damon, H. W. Stoudt, A. L. Moseley, J. W. Dunlap, and W. A. Hall, *Human Body Size and Capabilities in the Design and Operation of Vehicular Equipment*, Harvard School of Public Health, Boston, 1953.

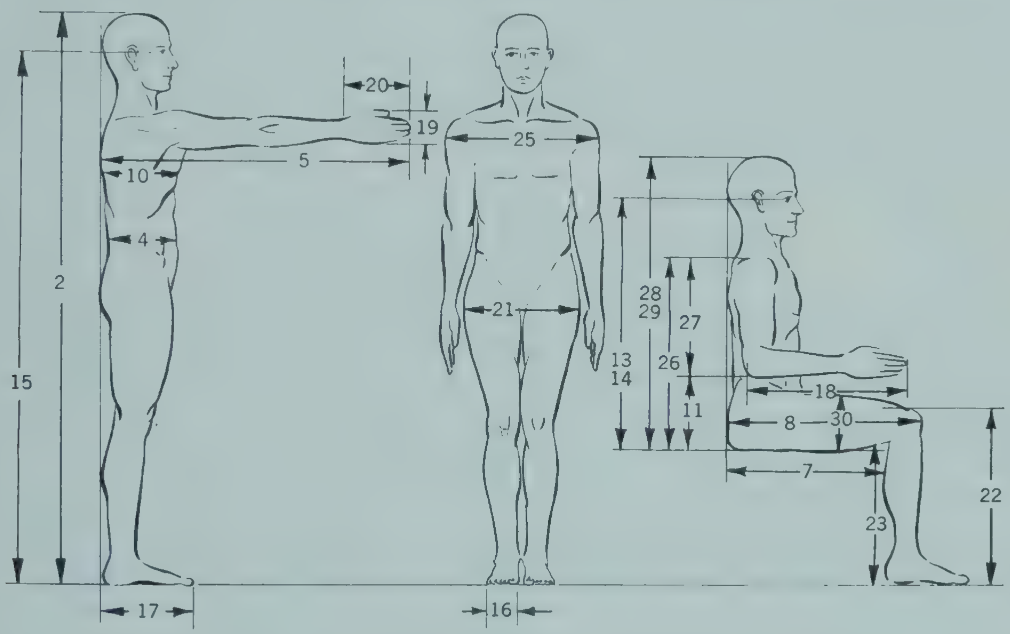

Figure 1. Body measurements applicable to various kinds of equipment design. The individual dimensions may be identified by number. See Table 1 for the means and standard deviations of these measurements for selected groups. (After Randall *et al.*[17])

It should be remembered that many industrial occupational groups are highly selected, differing from other groups and from the general public as well. Therefore the population that will use a given machine should be measured directly, if it is at all possible to do so. This is good practice, especially where limitations of weight and space have been imposed upon the designer. An example of using noncomparable groups would be the application of measurements taken on men only, when designing equipment to be used by a mixed population. Other difficulties will arise when an equipment dimension satisfactory for one condition conflicts with the requirements for a different condition. For example, Hooton studied a series of 3,867 people, using approximately equal numbers of both sexes, to determine the dimensions of seats for railway passengers.[12] He states that a seat depth of 20 inches would be sufficiently long to accommodate 90 per cent of the combined series including 85 per cent of the total males, and 95 per cent of the total females. However, this same 20-inch seat length would also mean that 15 per cent of the males and 40 per cent of the females would have to sit at least 2 inches forward from the back of the seat in order to bend their knees at right angles.[12]

Some selected static body dimensions for various groups are presented in Table 1.[11–15] Many of these values may be applied directly to industrial safety design. For example, the data are generally satisfactory for determining the sizes of protective clothing and equipment, as well as the resulting body clearances needed. Means (averages) and standard deviations are presented for each of the measurements (see below). Further information on the measurements, the points on the body from which they are made, as well as the instruments and techniques employed may be found by reference to such works as "Anthropometry of Flying Personnel"[13] or "Human Body Size and Capabilities in the Design and Operation of Vehicular Equipment."[11]

2. Utilizing Anthropometric Data

a. "Average" Values. The anthropometric data in Table 1 are presented in terms of average (arithmetic mean) values, a measure of central tendency that is quite familiar to everyone. However, in most problems of engineering design where the objective is to make the machine or the workspace fit the man, the average cannot be employed directly because this value gives no indication of the range at the top and bottom of the group. If only averages were used in the design of a vehicle, it is likely that as many as 50 per cent of the group would find many of the arrangements unsatisfactory for their use. For example, a knee clearance just large enough for the average man will be too small for the 50 per cent who are above average; and a control just reachable by the average man will be too far away for the 50 per cent who are below average.[16] As a further complication, the concept of the "average" man is unsatisfactory for design pur-

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[12] E. A. Hooton, *et al.*, *A Survey in Seating.* Heywood-Wakefield Corp., Gardner, Mass., 1945.

[13] H. T. E. Hertzberg and G. S. Daniels, Anthropometry of flying personnel—1950, *WADC Tech. Rept. 52-321,* Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1954.

[14] R. W. Newman and R. M. White, Reference anthropometry of army men, *Report* No. **180,** Environmental Protection Section, Research and Development Branch, Military Planning Division, Office of the Quartermaster General, Dept. of the Army, 1951.

[15] G. S. Daniels, H. C. Meyers, and S. H. Worrall, Anthropometry of WAF basic trainees, *WADC Tech. Rept. 53-12,* Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1953.

[16] B. G. King, Measurements of man for making machinery, *Am. J. Phys. Anthropol.* **6,** No. 3, 341-351 (1948).

TABLE 1. Some Selected Body Measurements Applicable to Equipment Design. (In inches)

	Males								Females			
	U. S. Army N = 24,465[14]		U. S. Air Force N = c. 4,000[13]		Civilian truck and bus drivers N = 271[11]		Civilians—general population[a] N = 1,959[12]		U. S. Air Force N = 852[15]		Civilians—general population[a] N = 1,908[12]	
	Mean	S.D. (σ)[b]	Mean	S.D. (σ)[b]	Mean	S.D. (σ)[b]	Median	Q.D.[c]	Mean	S.D. (σ)[b]	Median	Q.D.[c]
1. Age	c. 22		28.87	4.22	38.86	8.13	38.5		19.79	2.71	35.6	
2. Stature	68.47	2.51	69.11	2.44	68.33	2.41	69.0	1.95	64.07	2.34	64.9	1.70
3. Weight (lbs.)	154.76	20.49	163.66	20.86	166.90	27.93	166.7	16.95	123.27	14.54	133.1	14.50
4. Abdomen depth			7.94	.88	9.64	1.37						
5. Arm reach, anterior (maximum)			38.59	1.90	35.50	1.69						
6. Arm span			70.80	2.94	70.75	2.69						
7. Buttock-calf length (seated)							18.9	.65			18.2	.70
8. Buttock-knee length (seated)	23.40	1.12	23.62	1.06	23.72	1.12						
9. Buttock-leg length (seated)			42.70	2.04								
10. Chest depth			9.06	.75	8.94	.94						
11. Elbow height (seated)			9.12	1.04			9.6	.60			9.7	.60
12. Elbow breadth	17.54	1.54	17.28	1.42	17.91	1.68						
13. Eye ht. sitting erect			31.47	1.27								
14. Eye ht. sitting normal					29.36	1.20						
15. Eye ht. standing erect			64.69	2.38								
16. Foot breadth	3.87	.24	3.80	.19	3.98	.20			3.58	.20		
17. Foot length	10.43	.47	10.50	.45	10.49	.50			9.43	.46		
18. Forearm hand length	18.73	.87	18.86	.81	18.68	.89						
19. Hand breadth	3.42	.19	3.48	.16	3.44	.18			3.02	.19		
20. Hand length	7.58	.36	7.49	.34	7.55	.33			6.76	.34		
21. Hip breadth	13.95	.90	13.17	.73					13.80	.95		
22. Knee ht. (seated)	21.62	1.09	21.67	.99	21.64	.99						
23. Popliteal ht.[d]			16.97	.77			19.0	.60			18.1	.60
24. Seat breadth			13.97	.87	14.55	1.08	15.3	.75			14.6	.70
25. Shoulder breadth	17.95	.99	17.88	.91	18.33	.97	17.6	.45			15.7	.60
26. Shoulder ht. (seated)	23.01	1.17	23.26	1.14	23.67	1.00						
27. Shoulder-elbow length	14.28	.81	14.32	.69	14.67	.70						
28. Sitting ht., erect	35.77	1.34	35.94	1.29	36.22	1.16						
29. Sitting ht., normal					34.40	1.29						
30. Thigh clearance (seated)			5.61	.52								

[a] Dimensions include street clothes (minus topcoats) and shoes.

[b] S.D. (σ) = standard deviation: one S.D. above and below the mean will normally include 68 per cent of the population; two S.D.'s, 95 per cent; and three S.D.'s, over 99 per cent.

[c] Q.D. = quartile deviation: one Q.D. above and below the median will include 50 per cent of the population.

[d] Height from floor to underside of thigh behind knee.

poses since he may be representative of the average in only one or a few of his physical dimensions. To illustrate, civilian males 69 inches tall (median value) have seat lengths throughout a range of about 17 to 21 inches and back heights that vary from about $26\frac{1}{2}$ to 31 inches so that the term "average" must be specifically qualified if it is to be of use for design purposes.[17]

b. The Standard Deviation. Owing to the numerous objections to the use of only average values in equipment design, a second statistical value, the standard deviation (S.D. or σ) is presented for the data in Table 1. This measures, in the same unit as the average or mean, the extent to which the individual values are scattered within the group. Sixty-eight per cent of any normal group will fall within the range of one standard deviation above and below the mean. A range of plus and minus two standard deviations will include 95 per cent of the whole series, and three standard deviations will include well over 99 per cent. Hence an inspection of both the mean and standard deviation of a normally distributed group indicates roughly how large a percentage of this group can be accommodated by a given measurement. For example, consider the body measurement of normal sitting eye height for commercial vehicle drivers (see Table 2). This is an important dimension used to establish the minimum and maximum allowable eye levels for adequate visibility and comfort. For this group the mean is 29.6 inches with a standard deviation of 1.2 inches. Thus, one can tell immediately that 68 per cent of the group have a normal seated eye level between 28.4 and 30.8 inches; 95 per cent between 27.2 and 32.0 inches and over 99 per cent between 26.0 and 33.2 inches.

c. The Percentile Table. In general, however, the most effective means of presenting data useful to the design engineer is the percentile table, a statistical device that can present the numerical values for a given dimension for any selected percentage of the population. Often the data may be given at 5 per cent intervals from the 5th percentile (only 5 per cent are smaller) to the 95th percentile (only 5 per cent are larger). Table 2 and Figure 2 illustrate this technique with regard to normal sitting eye height in commercial drivers. Thus a glance at the table shows not only the average or median value for this dimension but also the range for any given percentage of the population. With the aid of percentile distribution tables for certain selected human body dimensions, a given piece of equipment can be evaluated to determine what percentage of the operator population can be adequately accommodated in those dimensions, from the points of view of safety and efficiency. Examples might be the varying dimensions of the seat; height of a bench or table; various reach distances for controls, tools, or other items; location of eye level for adequate visibility; etc.

d. Correlations. Correlation tables of anthropometric dimensions show how one body measurement varies in relation to another measurement. For any given

[17] F. E. Randall, A. Damon, and D. I. Patt, Human body size in military aircraft and personal equipment, *AAF Tech. Rept. 5501*, Air Materiel Command, Wright Field, Dayton, Ohio, June, 1946

TABLE 2

Normal Sitting Eye Height[11]
(Distribution in percentiles)

Percentiles	Inches (civilian drivers)
5	27.72
10	28.11
15	28.39
20	28.58
25	28.74
30	28.98
35	29.13
40	29.29
45	29.45
50	29.61
55	29.72
60	29.88
65	30.00
70	30.16
75	30.43
80	30.55
85	30.75
90	30.98
95	31.61

Number 309
Range: 26.38–32.68
Median: 29.61

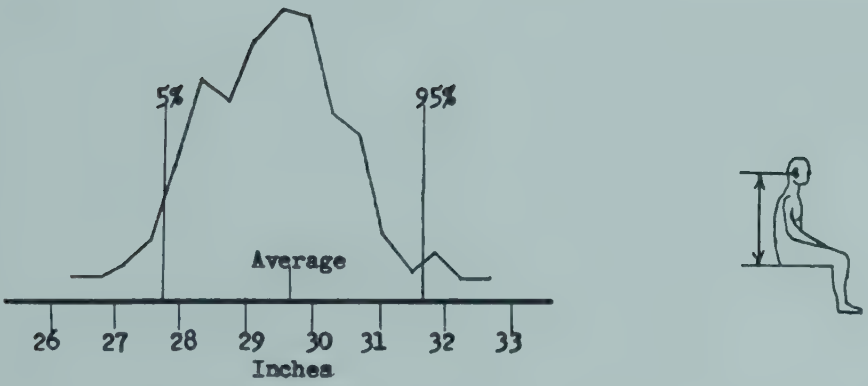
Civilian Drivers

Figure 2. A graphic presentation of the data in Table 2. The eye height of 90 per cent of the group, 5th to 95th percentiles, varies from 27.7 to 31.6 inches, a range of about 4 inches. Assuming a single eye level for optimum visibility, 4 inches of vertical adjustability should be provided in the seat in order to accommodate this portion of the group. If only a single seat height is provided, based on the "average" eye level height, it may be 2 inches too low for the short man or 2 inches too high for the tall man. These measurements apply specifically to commercial bus and truck drivers and will probably differ for other working groups. (From McFarland *et al.*[11])

value of one dimension, the corresponding range of values for a second dimension can be determined. The use of such tables can sometimes help to avoid the unnecessary consideration of some of the many individual body measurements that might be pertinent to the design of a piece of equipment. In general, stature correlates reasonably well with body heights and lengths, and weight with breadths, depths, and circumferences.[18] A person of the 5th or of the 95th percentile in height and weight will tend to approximate (but not necessarily duplicate) the 5th or 95th percentiles in his other measurements. Thus, if the height and weight of a group are known, and these measurements are easily taken, *approximations* of some of their other body dimensions may be obtained by referring to correlation tables for this group or even for roughly comparable groups. These have been worked out extensively for the military population by Newman and White. However, it cannot be too strongly emphasized that the correlations are not high enough to permit precise individual prediction, but only group prediction. With intergroup comparisons there is an added factor of error. For these reasons measurements of the dimension involved are always preferable in situations where any degree of precision is required.

3. Dynamic Body Measurements

So far the discussion of anthropometric measurements has centered around the static dimensions of the human body. Although these dimensions are helpful in solving many problems of human sizing in equipment operation, it is evident that a man never operates his machine in the rigid nude positions in which his measurements are taken. For this reason additional material on the dimensions of the human body under dynamic conditions is necessary. To take the most obvious case, clothing can and does alter a man's weight and dimensions considerably. For example, if precise values of weight are required, it is necessary to add allowances for the type of clothing worn while working and for the weight of pocket contents. For men, street clothing may weigh 4 to 8 pounds. While the total increases in the example cited may amount to only about 5 per cent of the nude weight, the specification of a precise reference weight may be important for design purposes; for example, if an engineer adds a percentage safety factor to the strength of a structure based upon a nude reference weight that safety factor would obviously be less than intended. The percentage difference might not be great but situations can be readily visualized where such differences may be of practical importance, for example, when establishing limitations for the number of people occupying an elevator or a vehicle; in conservation of critical materials; or in transport equipment where weight penalties must be reduced to a minimum.[2]

In addition to increasing weight, clothing increases body dimensions, and in some cases restricts the range and distance of movement as well, as in functional arm reach. With light summer clothing such changes may be negligible, while with heavy winter clothing the differences may be considerable. Other applications in which differences for clothed and unclothed dimensions might be significant would be calculation of area of contact from anthropometric descriptions of the hands and feet, as well as clearance between hand controls, and clearance for pedals or foot-operated controls.

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[18] R. A. McFarland, A. Damon, and H. W. Stoudt, *The Application of Human Body Size Data to Vehicular Design*. Special Publication 142. Soc. Automotive Engrs., 1955.

Of greater general importance, however, in the over-all concept of dynamic dimensions is the fact that variations in certain body measurements can influence an employee's ability to perform those movements or actions required for the safe operation of his mechanical equipment. For example, the location of a control for a large man might well be grossly inadequate for a much smaller operator. In cases such as this, one of two courses of action may be taken. Either (*1*) the control must be relocated so as to be equally accessible to both the largest and smallest men, or, if this is not feasible, (*2*) adjustability must be built in at one end of the machine dimension, either at the control itself or at the seat or standing area of the operator.[19]

In considering the whole problem of the functional human dimensions pertinent to the safe design of mechanical equipment, it becomes apparent that the basic data needed, in addition to the static body dimensions in the working position, are of three types: (*1*) the eye level of individuals in the working position; (*2*) the maximum arm reaches, in various vertical and horizontal planes, that can be attained without altering position, and the extension of these reaches attainable by further movements of the trunk or body; (*3*) the leg reaches that can be attained without altering position.[16]

a. Normal Seated Eye Level. This is a basic measurement of considerable importance in the design of working areas of industrial equipment. The eye position of the operator will determine, in part, how much of his surroundings he will be able to see, and how well he will be able to see it. Many working areas have a limited zone in which the operator's eyes will be able to supply him with the necessary visual information most efficiently. The disadvantages of an eye level too low or too high are obvious in the case of vehicular equipment, for example. Where such conditions exist, the designer must see that the spatial relationships of the working area are redesigned so as to permit optimum visibility. This cannot be done, however, unless he first knows at what height above a given seat level the operator's eyes will be located. Although it might seem that seat to eye height would be a fairly straightforward static anthropometric measurement, the problem is complicated by the fact that nearly everyone has a pronounced "slump" when sitting in a comfortable position for operating equipment. However, only two occupational groups have been directly measured for normal sitting eye height. One is a group of commercial truck and bus drivers who averaged 29.36 inches in this dimension.[11] See Table 2 for the distribution of the series. In the other series 100 male employees of the Civil Aeronautics Administration averaged 29.66 inches with a standard deviation of 1.24 inches. In another male series of 4,000 AAF flying personnel on which sitting eye height, *erect*, was taken, the average was 31.47 inches with a S.D. of 1.27 inches.[18] For this series, however, a correction factor may be subtracted to adjust for the probable slump in normal sitting eye height. This factor, or difference, between erect and normal seated posture, has been variously determined as follows: (*a*) two studies at Wright Field showed an average of 1.2 inches;[20] (*b*) 360 commercial truck and bus drivers averaged 1.8 inches;[11] (*c*) 131 civilian pilots showed an average of 2.25 inches.[21] In general, those with smaller sitting heights will have a smaller than average slump while those with large sitting heights will be above average in slump.

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[19] J. H. Ely, R. M. Thomson, and J. Orlansky, "Layout of Workplaces," in *Joint Services Human Engineering Guide to Equipment Design*, Wright-Patterson Air Force Base, Ohio, 1956, Ch. V.

For women, only two small series of *erect* sitting eye height are available: 443 female pilots averaged 30.0 inches, while 151 nurses averaged 29.3 inches.[17] No direct information on slump is available, but it might be tentatively assumed that the average would be slightly less than those observed for males.

b. Arm Reaches. One limiting factor in establishing the dimensions of any working area, including the location of controls, tools, and materials, is the functional arm reach of the operator. It might seem that the static body measurement of anterior arm reach could be used as an indication of the maximum boundaries of the working area for the location of hand controls. However, this dimension defines only the very limited reach area directly in front of the shoulder. Reach to a vertical plane in front of the worker falls off rapidly as the arms are moved to the sides or up and down. Moreover, there is no completely satisfactory way of predicting functional arm reach from anterior arm length or any other single static dimension because of the numerous other variables involved, such as individual differences in sitting heights, shoulder breadths, and variations in the biomechanics of movement at the shoulder. Owing to these difficulties most of the research in this field has been directed toward the study of specific installations for specific populations rather than toward more generally applicable descriptions of biomechanics and human abilities. This is not difficult to understand since the human body is so complex that a formidable number of descriptions would be required in order to provide information for the solution of a significant percentage of industrial situations. It is necessary to develop orderly summaries of the degree of movement, the precision of movement, and the force of movement of the component parts of the body with and without supplementary body support and with various degrees of flexion, extension, rotation, adduction, and abduction.

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[20] D. L. Patt. Cockpit dimensions in relation to human body size. *TSEAL-3-695-27*, ATSC, USAAF, April 29, 1945.

[21] B. G. King and J. J. Swearingen. Some biological factors in the design of civil aircraft. *J. Aviation Med.*, **19,** 414–419 (1948).

The easiest type of functional arm-reach data to obtain is that concerned with only a single horizontal or vertical plane. On horizontal surfaces two "reach" zones may be defined. First, there is a normal reach zone in which work can be done most easily without the use of the upper arm. Second, there is a maximum reach zone that extends to the points of maximum arm reach. In general, of course, controls, tools, or materials that must be handled often or accurately should be located within the normal reach zone. Secondary items or controls, used only occasionally, may be located beyond the normal reach zone but within maximum reach. Figure 3 shows a drawing of the dimensions of these normal and maximum working areas as constructed by Barnes. The zones, he believes, should be applicable to about 95 per cent of the adult working population. For some selected occupational groups, or for segments of the general population larger in body size, these dimensions could be increased. It will be noticed that the reach areas for each arm are semicircular in shape. Work requiring two hands must be located within the overlapping areas of the right and left hands.[22]

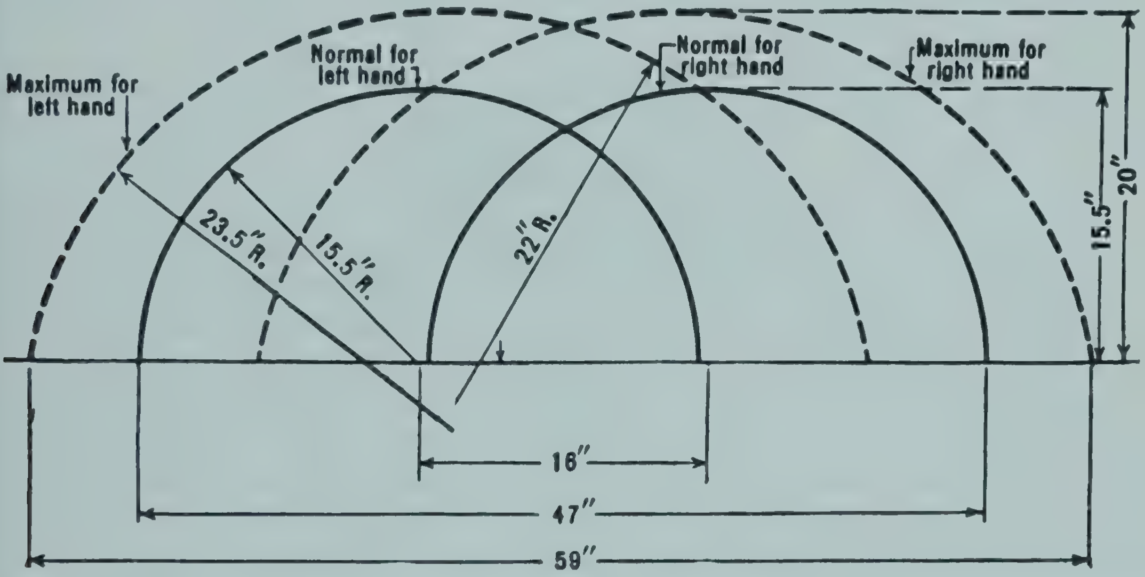

Figure 3. The normal and maximum working areas on a horizontal surface as determined by measurements made on 30 males. The areas are shown for the right and left hands working separately, as well as for both hands working together. (Reprinted with permission from Ralph M. Barnes, *Work Methods Manual,* 1944, John Wiley and Sons, Inc.)

The maximum reach to a vertical plane in front of the operator will lie directly in front of the shoulder. As the arms are moved to the right and left, or up and down from this point, decreasing portions of the vertical plane will fall within a given reach zone. In general, this zone will approximate a circle whose size will vary depending on the arm reach of the operator.[23]

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[22] R. M. Barnes, *Work Methods Manual.* Wiley, New York, 1944. See also P. C. Squires, The shape of the normal work area, *U. S. Naval Medical Research Laboratory, Report No. 275,* New London, Conn., 1956.

More often than not, however, a knowledge of arm reach to a three-dimensional region is required rather than to a vertical plane only or horizontal plane only.[24] Functional arm reach for many working areas will, in general, correspond to the illustration shown in Figure 4. One investigator who has dealt concretely with problems of this complexity is Dr. B. G. King. In the experimental method employed to determine the various reach measurements, a series of seated subjects reached for and touched successive points on a vertical measuring rod as it was brought forward along a horizontal support. Horizontal distances from the vertical line rising from the seat reference point to the vertical measuring rod at extreme fingertip reach were measured for each of 99 points. The over-all pattern is such that the average reach increases as the arm is moved laterally from 0° to 15, 45, 75, 100, and 105° and decreases as the arm is raised or lowered from the trunk height of the subject (see Figure 5). The unequal radii of any arc describing various successive points of reach are attributable to the position of the shoulder joint in relation to the mid-sagittal plane of the body and to its architecture. Data on the maximum distance that could be reached by 97 per cent of a Navy male population are presented in Table 3.[25] Distances are

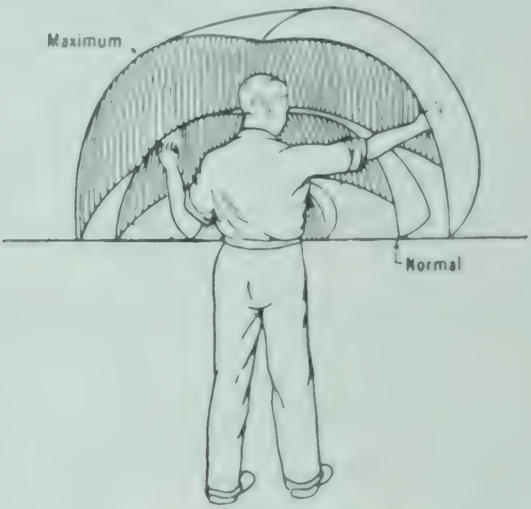

Figure 4. The normal and maximum working areas in three dimensions. (Reprinted with permission from Ralph M. Barnes, *Work Methods Manual*, 1944, John Wiley and Sons, Inc.)

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[23] H. L. Lipschultz and K. O. W. Sandberg. Maximum limits of working areas on vertical surfaces. Office of Naval Research. Special Devices Center. *Report No. 166-I-8*, 1947.

[24] A. Chapanis, W. R. Garner, and C. T. Morgan. *Applied Experimental Psychology. Human Factors in Engineering Design.* Wiley, New York, 1949.

[25] B. G. King, D. J. Morrow, and E. P. Vollmer. Cockpit studies—the boundaries of the maximum area for the operation of manual controls. *Project X-651, Report No. 3*, Naval Medical Research Institute, National Naval Medical Center, 1947.

TABLE 3
Maximum Reach with Right Arm
(In inches)

Level above reference point (in.)	Angle			
	0°	R 15°	R 45°	R 75°
46	11.6	13.7	15.0	17.0
40	18.9	20.5	22.4	24.1
34	22.9	24.9	26.6	28.0
28	25.5	27.1	29.1	30.1
22	26.7	28.2	30.3	31.4
16	26.6	28.0	29.7	31.6
10	25.3	27.0	29.3	30.4
4	22.6	24.2	26.4	27.9
−2	17.5	19.7	21.8	22.8

measured from the vertical line through the reference point with the subject's shoulders touching the back cushion; seat back 13° from the vertical. The reference point is at the upper level of the seat cushion at its line of intersection with the lower cushions of the back. Reach for the left arm can be outlined by using above measurements at corresponding points to the left (see Figure 5).[25]

Unfortunately, there are two limiting factors that prevent these data from having wide applications in general problems of equipment design. The first difficulty is that the sample consists only of male Naval personnel. Although King believes that they may be sufficiently representative to serve as a basis for specifying reach dimensions satisfactory for a relatively large percentage of a random sample of men in the armed forces, nevertheless they will not necessarily closely approximate other selected populations. For example, the functional reaches that can be maintained by 93 per cent of this Naval group might be achieved by only 75 per cent or perhaps by as many as 98 per cent of other groups.

It should be remembered also that reach dimensions will change with any alteration in the conditions of the working area, such as a difference in the inclination of the seat or seat back, thus necessitating either a new study under the new working conditions or the computation of correction values to be applied to the table of standard data. An additional point is that the dimensions in Table 3 are maximum reach measurements taken at the fingertip. Obviously controls cannot be operated at these extreme locations. Depending upon the characteristics of the control and the degree of movement and accuracy required, its maximally distant location may be up to 5 inches less than the outermost range of fingertip reach.[25]

The above necessary qualifications and restrictions point up the complexity of functional arm-reach problems and the difficulty of applying specific dimensions to all situations. However, it should be remembered that a limited use of such correlations as exist between arm length or reach measurements and other body

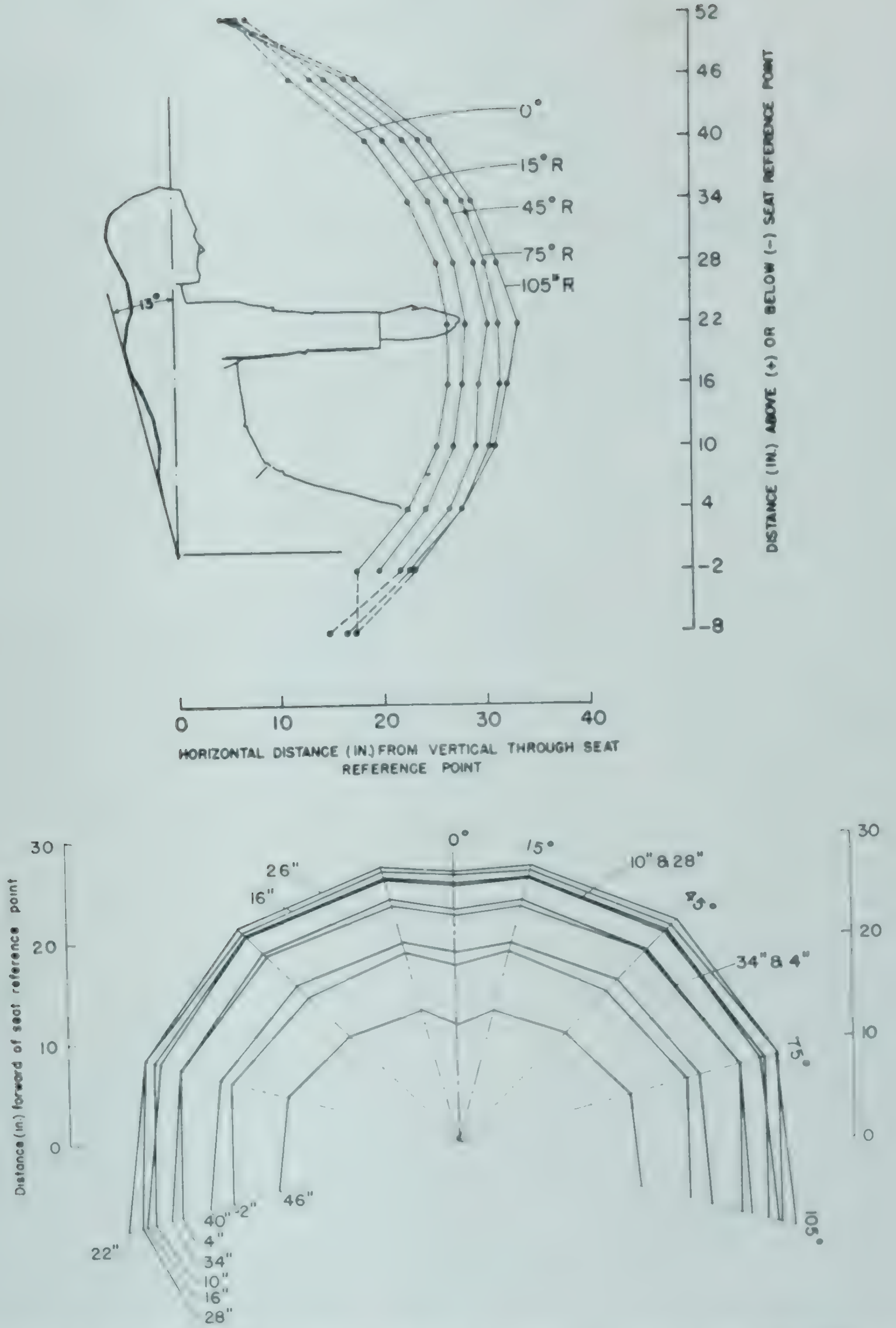

Figure 5. Maximum reach distances shown in vertical (upper) and horizontal (lower) planes. Degrees refer to angles to the right or left of the midline of the body, and inches refer to distances above or below the seat reference point. The reference point is established at the intersection of the upper level of the seat cushion with the small lower cushions of the back pad. These reach dimensions were attained by 97 per cent of a U. S. Navy group, but they will not necessarily be applicable to other groups differing in body size. (From King *et al.*[illegible])

dimensions such as height or weight can permit general predictions for groups of people who will use the machine, although they may be inaccurate as far as individuals are concerned. In vehicle cabs, for example, where seat adjustability is present, the correlations of body dimensions indicate that tall, long-legged drivers who adjust their seats in rearward positions will in general also have correspondingly longer arms and will be capable of the increased reaches required from their rearward seat locations. In like manner men with shorter legs who are in more forward positions will not need to reach as far with their shorter arms.[18]

Where it is possible to run experimental tests with a mock-up of the working area in which the more important items are completely adjustable, a simpler, though practical, procedure may be used to determine design dimensions compatible with functional arm reach. Selected individuals of the 5th, 50th, and 95th percentiles in their body dimensions are used as test subjects in different design layouts. The specific measurements most pertinent to this purpose are anterior arm reach, normal sitting eye height, shoulder breadth, and weight. All subjects should be dressed in the heaviest clothing normally worn, which may reduce functional arm reach by as much as 1 inch. If possible, all controls or materials should be located in positions where they can be easily reached by all workers within the given size range without moving from their normal position. Consideration should be given not merely to the maximum and normal boundaries of reach but to direction and distance of reach as well, in order to insure the swiftest and most efficient operation. Possible obstructions to free arm movement, to the sides as well as the front, also should be considered. Those controls or materials used most often, or those of a critical nature, should naturally be given priority in their location. This empirical technique is applicable not only to problems of arm reach, but to all situations in which some aspect of dynamic dimensions is involved.[11,18] Figure 6, for example, shows the nine adjustments used in one mock-up study to determine the dimensions and spatial arrangements of truck cabs.[26]

c. Leg Reaches. In those industrial tasks in which the workers' legs perform no controlling functions, there will be no anthropometric problem other than that of providing sufficient room for comfort and to avoid cramping or crowding. This is basically a matter of simple clearances based on static human dimensions plus added allowances to permit changes of leg positions. Where foot controls, such as pedals or treadles, must be operated, however, additional considerations are necessary, although they are generally of a simpler order than are those concerning the location of hand controls. In few industrial tasks are the legs required to operate more than two or three pedals. Since these can usually be located to the front of the operator, on or about floor level, the basic anthropometric problem is simply one of forward leg reach, a function of leg length. The one means of providing for variations in workers' leg length is through the adjustability of the dimension between the foot controls and the seated position of the worker.

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[26] N. C. Kephart and J. W. Dunlap, *Human Factors in the Design of Vehicle Cab Areas.* Occupational Research Center, Purdue University, 1955.

Although there is the possibility of making the controls themselves adjustable, it has generally been found easier and more satisfactory to have a range of front-to-back adjustability in the seat. The amount of adjustability will depend upon the range of leg length of the population operating the machine. To give a concrete example, it was found that $6\frac{1}{4}$ inches of adjustability was completely adequate for 90 per cent of all commercial bus and truck drivers.[26] With other populations, as where small women are using the same equipment as large men, the range would be greater. This engineering problem occurs only when the seat is a fixed part of the working area, as in vehicular equipment; where the seat is a movable stool or chair, a wide range of positions is usually feasible, and the problem can be solved much more simply.

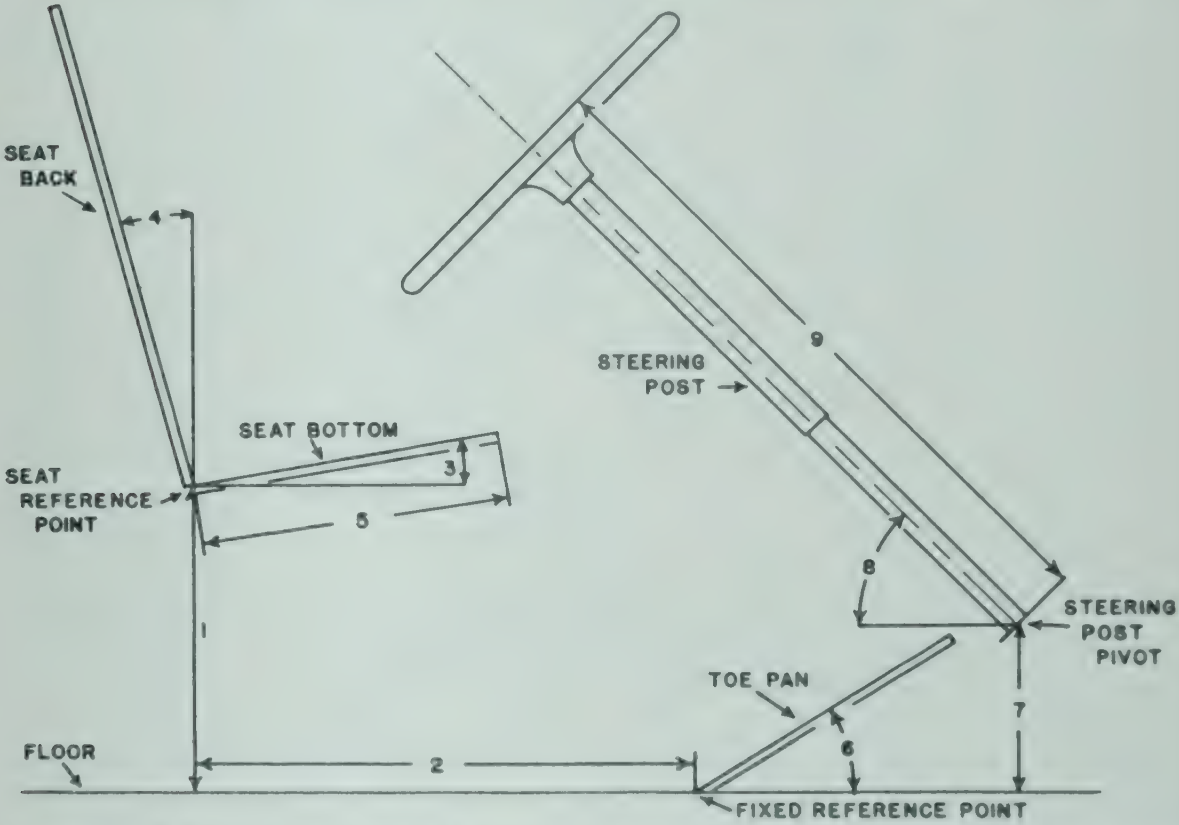

Figure 6. Schematic diagram of a mock-up truck cab designed to determine the various adjustments and arrangements required by a population of a given range in body size. A similar mock-up could be designed for almost any kind of equipment or working area. (From Kephart and Dunlap.[26])

d. Seating Dimensions. In those industrial tasks that require or permit a seated position, the most efficient and comfortable design of seats and chairs is essential. This necessitates the use of a special group of body measurements, many of which are basically static in nature, such as seat breadth. However, additional factors, including clothing increments, room for changing of positions, and body clearances during the operation of controls, require a partially dynamic treatment of the problem. The location, dimensions, and adjustability of the seat should be considered with reference to the arrangements and location of the tools, materials, controls, and displays used by the person. In addition, the seat must afford the operator maximum comfort, consistent with efficiency, in order to reduce fatigue. Functional, comfortable seat design can do much to add to the efficiency and safety of job performance.

In seat designs, equally as much as in other aspects of equipment design, the population that is to use the equipment must be measured directly. For this reason it is difficult to make specific recommendations applicable to industry in general. To give an extreme example, some of the seat dimensions and locations adequate for female factory workers would be most unsatisfactory for a substantial percentage of the size range of commercial truck drivers. What will be emphasized here are the pertinent body dimensions and design principles relevant to seat construction. Some specific figures will be given, based on data drawn from different segments of the population. The dimensions and characteristics of the seat that must be considered include the breadth, depth, height, slope, and shape of the seat and back rest.

Seat breadth. This dimension is one of the easiest to establish and can be based on the seat breadth of the individual as measured across the buttocks when in the seated position. In a study of the seating problem in industry, Garner has stated that the breadth need be only 16 to 17 inches.[27,28] These may be acceptable as minimum figures, but if changes of seated position are occasionally possible or desirable, and if all but the very broadest of male workers are to be included, a breadth of 19 inches will be more satisfactory.

Seat depth. The most important single consideration in seat depth (length) is that the parts of the hip bones that bear the weight of the seated body (the ischial tuberosities) should be properly supported. A depth of as little as 8 to 10 inches will be sufficient for this purpose, a requirement fulfilled by almost all industrial seats. If the seat depth is excessive, workers with shorter legs will find the front edge of the seat cutting into the back of the calf, and will be unable to bend the knee satisfactorily unless they shift their buttocks forward on the seat. On the other hand, long-legged workers will have inadequate thigh support if the seat is too short. The upper limit for this dimension can be determined from the thigh length of the smallest segment of the population to be accommodated, as measured from the back of the calf to the plane of the back while in the seated position. The 5th percentile of a large series of the general population was 17.0 inches in this dimension (males 17.4, females 16.8).[12] A seat depth greater than

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[27] J. R. Garner, Posture in its relation to industrial fatigue, *Med. J. and Record,* **138,** 73–77 (1933).

[28] J. R. Garner, Fatigue in its relation to accident prevention, *Ind. Med.,* **6,** 665–668 (1937).

this would not be feasible unless there were no disadvantages entailed in sliding the buttocks forward in the seat. It should be noted that Garner,[27,28] in two studies of industrial seating, believes that a depth of 11 inches will be ample.

Seat height. The height of the seat above the floor is most important to the comfort and efficiency of the worker. This is particularly true with excessive heights, which will cause pressures of a more or less injurious nature on the muscles and nerves of the under part of the thigh. Consequently, the seat should be sufficiently low to insure that the thighs can be kept free or almost free of the seat. This does not mean that a person may not find it comfortable to rest his thighs on the seat at times, but in general this is not a suitable position for extended periods. The pertinent body measurement in this case is taken from the floor to the tendons of the thigh in back of the knee (popliteal area) when the subject is in the sitting position.[29] In the general population, this body dimension (including shoe thickness) measures 16.9 inches for the 5th percentile or shortest group (men 17.6, women 16.7).[12] It is obvious that the maximum seat height should not exceed these figures; 1 inch less would be more satisfactory. If the legs must be extended forward for the operation of foot pedals, lower leg height is reduced, and it may be necessary to reduce further the height of the seat. Under most circumstances, provisions for the vertical adjustment of industrial seats will be both desirable and feasible. For many groups a 6-inch adjustability will be adequate, but since the requirements might vary considerably depending both on the body size range of the working population and on the type of work and movements required, it would be best to determine this range experimentally for individual situations.

Shape of seat. The shaped saddle-type seat with an elevation between the thighs generally has been found unsatisfactory since it requires the buttocks to be correctly fitted to the corresponding concavities of the seat. In theory, this would result in pressure being evenly distributed over the buttocks, a disadvantageous feature since both anatomical and physiological considerations make it desirable that the ischial tuberosities (the parts of the hip bones in contact with the seat) bear the larger part of the body weight. Edwards and Duntley have shown that the blood supply to the skin over the tuberosities is peculiarly adapted to weight-bearing.[30] The curvature of the tuberosities and their surface irregularity make it difficult to obtain definite measurements although, in general, they are slightly over 1 inch in breadth and about $1\frac{1}{2}$ to 2 inches in length. Although the distance between the tuberosities is approximately $4\frac{3}{4}$ inches in men and 5 inches in women, there is enough variation in the size and shape of the buttocks so that a given shaped seat would be uncomfortable for a large percentage of any population. A generally flat surface would be superior. Since the tuberosities are so small, there is little use in having a very soft and resilient seat, for a large amount of the weight would be transferred to tissues that are not adapted for bearing it. The best seat consistency, therefore, is one that gives only slightly under pressure.[29]

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[29] B. Akerblom. *Standing and Sitting Posture.* A. B. Nordiska Bokhandeln, Stockholm, 1948.

[30] A. E. Edwards and S. Q. Duntley, The pigments and color of living human skin, *Am. J. Anat.*, **65**, 1–34 (July, 1939).

Back rest. Two types of back rest may be used in industrial seating. One type consists of a large flat or curved surface that can support the entire area of the back. The back rest found in motor vehicles would be one such example. Provided only that they be about 18 to 20 inches high and about 20 inches wide, back rests of this type will be able to accommodate almost everyone in regard to the pertinent body dimensions.[18]

The second, and probably more common, variety consists only of a support for the lumbar region of the back, the area subject to the greatest strain. The typist's or stenographer's chair offers an example of this type of backrest. In such chairs it is desirable to leave a space below the lumbar support so that the buttocks can be shifted to the rear of the seat, thus giving a slight arch to the small of the back. Increasing or decreasing the arch in this manner creates further opportunities for the change of position important in maintaining comfort and in retarding the onset of fatigue.

The pertinent body dimensions in the construction of chairs with a lumbar support is the vertical distance from the seat to the top of the sacrum, at the position of the first lumbar vertebra. Fortunately, individual variation in this body dimension is slight, and the position of the lower edge of the lumbar support will be adequate if it is located no more than 7 to $7^1/_2$ inches above the level of the seat.[31] It should not be so high as to come into contact with the shoulder blades. In addition, the back rest should be curved to correspond as accurately as possible to the natural curvature of the lumbar region in the horizontal plane. On one male population, this curvature was found to approximate the arc of a circle of $7^5/_{16}$-inch radius.[32] If the back support is vertically adjustable, adequate provision can be made for virtually the entire population.

Slopes of seat and back rest. While the slopes of the seat and back rest are not primarily related to anthropometric measurements, brief mention of them should be made in any discussion of seat design. If the back rest is vertical it may give support to the small of the back, but it will be unable to support directly any of the weight of the body. When this is desirable, it is necessary to slope the back rest to the rear. More weight is carried by the back rest as its slope increases. In this way the supporting organs and muscles of the body will be relieved of part of their burden. Although the degree of inclination, if any, must vary with personal preference and job requirements, a slope in the vicinity of 115° from the horizontal is often found satisfactory. Under such conditions, if the seat is horizontal, pressure on the back rest will give rise to an opposing force that tends to push the buttocks forward on the seat. For this reason, the seat must have a front to rear downward slope, of perhaps 5 to 7°, although this too must remain a matter of experience.[29] It should be noted, of course, that the sloping of seats or back rests may be undesirable in jobs requiring special sitting positions or postures.

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[31] B. Akerblom, "Chairs and Sitting," in W. F. Floyd and A. T. Welford, eds., *Human Factors in Equipment Design.* H. K. Lewis, London, 1954, Ch. 5.

[32] A. G. M. Weddell and H. D. Darcus, Some anatomical problems in naval warfare, *Brit. J. Ind. Med.,* **4,** 77–83 (April, 1947).

4. Sources of Anthropometric Data

It has been emphasized in this discussion that it is often necessary to measure directly the population that will operate a given machine or perform a certain task because anthropometric differences among various industrial groups may be quite marked. Unfortunately, relatively few anthropometric studies have been made of specific occupational groups. In many instances, therefore, surveys of this nature must be undertaken before the workers' equipment can be truly "human-engineered." In some cases, where less precise descriptive material may be sufficient, a rough approximation of human dimensions for a given group may be obtained by consulting published anthropometric data on different series of individuals, especially if use is made of the concept of correlations between the various body dimensions (see page 68). Much of the existing data for American males has been taken on military populations. Newman and White, working with the United States Army Quartermaster Corps, have published the results of a comprehensive survey of 24,000 men in their "Reference Anthropometry of Army Men."[14] For the Air Force, two publications offer valuable data, "Human Body Size in Military Aircraft and Personal Equipment"[17] and the comprehensive "Anthropometry of Flying Personnel."[13]

For the general civilian population, Hooton has presented data on 8 body measurements especially pertinent to seat design for 1,900 males and 1,900 females in his *A Survey in Seating.*[12] Studies on the body dimensions of women are reported by O'Brien and Shelton in a United States Government publication, "Women's Measurements for Garment and Pattern Construction."[33] In this report, medians, means, standard deviations, and coefficients of variation for 59 measurements of over 10,000 women are given, together with tables of partial correlations of the various dimensions. Comprehensive anthropometric data directly pertinent to the design of desks, chairs, and other equipment for school children of all ages are available in *The Functional Body Measurements of School Age Children.*[34] For specific industrial occupational groups, data on the dimensions of commercial truck and bus drivers may be found in *Human Body Size and Capabilities in the Design and Operation of Vehicular Equipment.*[11]

At all times, however, it should be remembered that it is always preferable, and sometimes mandatory, to measure the working population directly before applying the data to the design and layout of industrial equipment

[33] R. O'Brien and W. C. Shelton. Women's measurements for garment and pattern construction. *Misc. Publication* No. **154**, Bur. Home Economics, U. S. Dept. of Agriculture, Washington, 1941.

[34] W. E. Martin and L. P. Thune. *The Functional Body Measurements of School Age Children.* National School Service Institute, Chicago, 1954.

III. Equipment Design in Relation to Human Capabilities

Much of the equipment within the working area can be divided into two main classes: displays and controls. Controls are those devices that govern the operation of the machines, and the problems that are associated with them are fundamentally those of the physiology and psychology of bodily movements. Displays are those devices that tell how the machines are functioning. Display problems are primarily concerned with the normal functioning of man's senses. Controls direct the input of the machines; displays show the output.[35]

A. VISUAL DISPLAYS

Accidents may occur because a worker has not clearly perceived the location or movement of the indicators, meters, or dials that relate to the functioning of his equipment. Very often one finds that special safety precautions have been taken with regard to one aspect of the working situation while little consideration has been given to other components of the job. Tasks may become uncomfortable and performance inefficient when an individual is required to perform a number of tasks successively or simultaneously, even though any single element of the job is easy to execute. The extent to which an employee receives clear and unambiguous information concerning all aspects of his job governs the way in which he exerts such controlling movements as the operation requires over long periods of time. "Visual Presentation of Information"[46] by Baker and Grether illustrates many of the principles of design of displays discussed below.

1. The Visual Field

In order to obtain the maximum information from the surroundings and from the displays, controls, and moving parts or materials within the immediate working area, a field of vision with the minimum of obstructions is necessary. The visual field of each eye, that is, the monocular field, ordinarily subtends a horizontal angle of about 160°, and a vertical angle of about 145°. In practice, the absolute size of the monocular field varies with the level of illumination, the size and color of the object viewed, and the age and condition of the viewer. The variations are described in a review by Hall and Greenbaum.[36] Owing to the considerable overlapping of the monocular fields the total field observed when both eyes are used subtends an angle approximately 200° in the horizontal axis; the use of both eyes does not, of course, influence the extent of the vertical axis. These limits apply when the eyes are fixed in their central position, as when looking straight ahead. Extreme movements of the eyes to one side and then to the other, with the head in its normal position, will enable a man to scan the surroundings to such an extent that his total "blind area" (at an adequate distance behind the viewer) is reduced to less than 30° to either side of the mid-line back of the head. Similarly, very moderate normal movement of both the eyes (15° to right and left of mid-position) and the head (45° to the right and left of mid-position) will enable a man to scan a total surrounding with a blind area of only 25° to the right and left of the mid-line of the back of the head.[36]

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[35] A. E. Javitz, ed., Human engineering in equipment design. *Electrical Manufacturing* Combined Reprint. Gage Publishing Co., New York, 1956. C. H. Best and N. B. Taylor, *The Physiological Basis of Medical Practice.* 2nd ed., Williams and Wilkins, Baltimore, 1940.

[36] M. V. Hall and L. J. Greenbaum, Jr., Areas of vision and cockpit visibility, *Trans. Am. Acad. Ophthalmol. Otolaryngol.,* 55th Annual Meeting, 74–88 (1950).

Since the retina of the eye is not uniformly sensitive, when the eyes are fixed, parts of the total visual field will be sufficiently distinct to permit discrimination while other areas will be much less distinct. While the peripheral areas of the retina are not useful for distinct vision, they do serve to direct the attention of the viewer to outlying objects and enable him to fixate such objects by appropriate movements of the head or eyes.

When it is necessary to see an object distinctly, both eyes fixate on that object so that its image falls upon corresponding portions of the retinas of the two eyes simultaneously. The area that includes the widest limits of vision in all directions on which the eyes can fixate for distinct vision is called the field of fixation; it implies that the head is fixed and that the scanning or succession of fixations result from conjugate eye movements. This area is found to be very nearly circular with a diameter of about 100°. Vision downwards is somewhat over 50°, which is slightly greater than in some other directions. The emphasis on design for layout of a work space so that the operator will be provided with as wide an area of view of his displays, machinery, and surroundings as possible does not imply that he is to be immobilized during operations. He should not, however, be required to make unnecessary, extensive, and inefficient movements.

2. Factors Affecting the Visibility of Displays and Other Objects

Regardless of which type of display is used in the working area, its visibility as well as that of tools and materials depends upon a number of well-known considerations. The most common of these factors are size of the object, the brightness contrast between it and its immediate background, the contrast between the task area and its surroundings, the brightness of the object itself, the length of time the object is seen, and the color of the illumination. Each of these factors is discussed briefly below.

a. Size of Critical Detail. Although the normal eye can detect very small objects, no operator should be expected to see or manipulate objects close to his visual threshold. Under such conditions, considerable discomfort and fatigue would result. A margin of safety should always be allowed with regard to the size of objects that must be seen or discriminated by the eye. The safety engineer should be well aware that visual details must be made considerably larger than the just-visible size.

b. Contrast between Object and Background. The greatest contrast occurs when a jet black object is on a pure white background or vice versa. Under such conditions of 100 per cent contrast, other things being equal, objects will be most visible.[37] Fortunately, the eye can get along comfortably with less contrast, but it is recommended that the contrast be kept at 75 to 80 per cent or higher if possible. Contrast may be used in a number of ways (either with black and white or colored paints) to augment the extent to which items will stand out from their background. Thus, frequently used tools, handles, danger areas, bins, switches, and so forth, can be made more visible by increasing their contrast.[2,24,71]

The question sometimes arises as to whether white on black or black on white is the preferable combination. Although many authorities maintain that the background should be lighter, data summarized by Fitts show that under night instrument conditions well-trained subjects read white figures on dark faster and more accurately than black figures of the same size on white. Where considerations of dark adaptation are important, instruments with white markings on black backgrounds keep the total bright area at a minimum and provide less peripheral glare when an operator is looking elsewhere. Berger has investigated number reading in daylight as well as at night, and he also found white on black superior, but numeral thickness was an added variable.[38]

c. Contrast between Task Area and Surround. The above principles regarding contrast may be incorrectly applied so that the working environment around the task areas is much darker than the area itself. Although it may seem advantageous to have the work locus "spotlighted" in the environment, there is greater eye comfort when the general environment around the working area is illuminated to the same degree as the background area.[37,39] Visual tests have shown optimal performance when the illuminations of the background and surround areas are equal. When that of the surround is less, there is a slow falling off of visual performance; when the surround illumination is greater than the background (as occurs with glare), visual efficiency falls off rapidly.[2,71]

d. Illumination. Much has been written about illumination, and there are numerous codes for lighting practice in schools, homes, offices, and industrial situations.[40] There has been a tendency to set the level of illumination as high as possible in the belief that vision will automatically improve with the amount of light. This is not always true, however, since the production of illumination above 50 footcandles is apt to cause glare points, specular reflections, high contrasts and shadows, and other deleterious effects in the periphery of the field of vision.[41] In some instances where the visual task involves discrimination of extremely fine objects (a lamp filament, for example), localized brilliant lighting by means of a special fixture can be used to "magnify" the work. Listed in Table 4 are some representative visual tasks and current recommendations believed to provide adequate levels of illumination (Cf. Chapter XX). For persons who have some slight eye disabilities or those with corrections, the lower levels in the table can be increased by 5 to 10 footcandles.[42] An increase in the illumination may be beneficial to persons in the older age groups.

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[37] P. W. Cobb and F. K. Moss, Lighting and contrast, *Trans. Illum. Eng. Soc.*, **22,** 195–204 (1927).

[38] Studies pertaining to the design of visual displays for aircraft instruments, computers, maps, charts, tables, and graphs; a review of the literature, *Tech. Rept. 5765,* Air Materiel Command, USAF, April, 1949.

[39] P. W. Cobb and F. K. Moss, Four fundamental factors in vision, *Trans. Illum. Eng. Soc.,* **23,** 496–505 (1928).

[40] American recommended practice of industrial lighting, *Illum. Eng.,* **37,** 275 (1942).

TABLE 4

Recommended Illumination for Various Types of Tasks[40,41]

Tasks comparable to	Recommended illumination (footcandles)
Reading legible print (10 point)	10–15
Sorting, rough inspecting, bookkeeping, reading newsprint	15–20
Setting 6-point type, stitching, gross assembly work	30–40
Severe industrial tasks, such as fine inspection, engraving, grading and sorting, proofreading	40–50

A number of devices are available for measuring illumination of the working area and its surrounding environment. Some of these depend on visual matching (for example, the Macbeth illuminometer), whereas others operate entirely on physical principles (for example, photocells of various types). When any type of photometer is used, it is important to remember that the illumination measurement should be made at the place at which the eyes look and not at the lighting fixtures that produce the illumination.

e. Time of Exposure. Many industrial jobs may not be affected by this variable, since the employee ordinarily can control the rate of his operations. In some jobs, however, such as high-speed assembly-line work or vehicle driving, the operator must obtain visual information very quickly. In these cases, there may not be time to detect the necessary information.[43] Fortunately, however, a drop in exposure time may be in part compensated for by increasing the illumination. Some of the other factors already listed also can be used instead of, or in conjunction with, illumination to overcome the loss of visual perception due to short exposure. Thus, one can increase the size of the visual detail, raise the illumination, increase the contrast, or decrease the glare when a fast operation depends on the use of the eyes. Whenever feasible, each variable should be used to its fullest extent. When this is impossible (as when time is short or the size of the visual detail is dictated by the operation itself), it should be recognized that other factors are available and can be utilized to create a more satisfactory visual display.[2]

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[41] M. A. Tinker, Trends in illumination standards, *Illum. Eng.*, **43**, 886–891 (1948).

[42] J. E. Kuntz and R. B. Sleight, Effect of target brightness on normal and subnormal visual acuity, *J. Applied Psychol.*, **33**, No. 1, 83–91 (1949).

[43] P. M. Fitts and R. E. Jones, Psychological aspects of instrument display: I. Analysis of 270 "pilot error" experiences in reading and interpreting aircraft instruments, AMC MR *TSEAA-694-12A*, October 1, 1947.

f. Color of Illumination. The use of color should be considered with reference to both normal and color-defective vision. Although the figures usually cited show that as many as 5 per cent of the male population are color-blind, recent estimates indicate that as high as 15 per cent of males may be "color-weak." The incidence of color blindness in females is much less. Many accessory visual aids, such as maps, charts, signs, and posters which have color designs, are unintelligible to color-blind individuals and sometimes may be confusing even to the color-normal.

In recent years, color has been used as an illuminant in incandescent or fluorescent fixtures and colored paints have been used for bench surfaces, walls, working materials, tools, and machines. It is necessary to distinguish among the purposes for which color is used in these various circumstances. In some instances, the primary interest is only that objects may be seen easily and comfortably. In other instances, color is used as a code or symbol to signify a particular bit of information (red for danger areas, green for electrical connections, black for tool handles, and so forth). In cases where colored lights are used as warnings, it is obviously important that the most easily discriminable colors be used. For viewing colored points of light, it has been shown that red, green, and blue are the most easily recognized, followed by white and yellow.[44]

One way of evaluating the effects of color is to compare the effectiveness of achromatic contrasts (such as black objects on a grey surface) with chromatic contrasts (such as green objects on a yellow background). Most studies have shown that achromatic contrast is a more powerful factor than chromatic contrast in producing discriminable effects.[45] In fact, the increased visibility that one obtains with the use of colors often can be attributed to the difference in brightness (achromatic contrast) between the colors rather than to the difference in hue. Thus, for maximal visibility, black on white or vice versa seems to be the best arrangement, although black and yellow have also been shown to produce good contrast.

3. Types of Visual Displays

Analysis of the different ways in which workers use visual displays indicates that three basic, but different, types of instruments should be used, according to the type of information required. The simplest type of information is concerned with whether the equipment is working normally or not. The indicator in this case need only be a warning signal (such as a green light to show things are normal, a red light to show danger or faulty operation). This is called a *check display*. A second type of required information is whether, and in which direction, a phase of an operation has departed from normal. Many dials showing revolutions, temperature, and pressure are used in this way. Since under normal working conditions all these functions should be within a certain range, it is possible to cover up the numbers and dial markings and mark off this range by heavy lines on the dial circumference. The operator then merely notes whether his pointer is within, above, below, or moving in a particular direction with regard to this range. This type of instrument is termed a *qualitative display*. A group of dials of this type may be arranged in a pattern to show at a glance which of several instruments may be malfunctioning. For this purpose they should be arranged in rows or columns so that their normal operating range is similar (see Figure 7).[24] The third and conventional type of indicator is called a *quantitative display*. Here the worker finds a numerical figure when he reads the display, as in speedometers or r.p.m. indicators. This type of instrument can give not only the direction but the rate of change as well. In many cases a quantitative indicator could be replaced by one of the other types. This sort of redesign should be one of the first considerations in the human engineering of visual displays.[2] When quantitative displays are used, however, they may consist of either a moving pointer with a fixed scale or a moving scale with a fixed pointer. For general purposes the former is most advantageous.[46]

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[44] N. E. C. Hill, The recognition of coloured light signals which are near the limit of visibility, *Proc. Phys. Soc. (London)*, **59**, 560–574 (1947).

[45] B. Ballamy and S. M. Nurhall, Attributive limens in selected regions of the Munsell color solid, *J. Opt. Soc. Amer.*, **32**, 465–473 (1942).

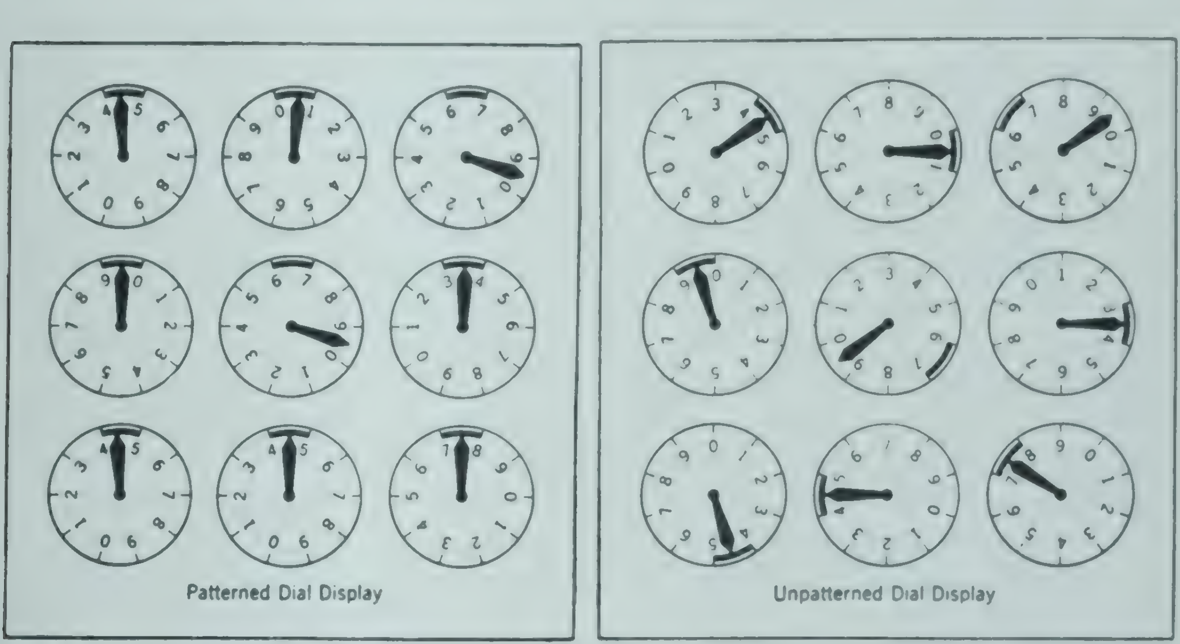

Figure 7. Patterned and unpatterned dial displays. Dials that are only required to indicate whether or not a certain activity is within a normal operating range may often be grouped together in a patterned display in which the normal pointer readings are oriented in the same direction. A quick glance can then determine which of many activities has departed from normal, as in the display at the left. In the unpatterned display at the right a much more time-consuming examination is necessary. (From Chapanis *et al.*[24])

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[46] C. A. Baker and W. F. Grether. Visual presentation of information. *WADC Tech. Rept. 54-160*, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1954

4. Principles of Display Design

In addition to general factors involving the visibility of objects within the working area, sufficient research has been done within the field of visual display design to warrant some fairly specific recommendations. The areas of research include shape, size, type of scale markings, distance between markings, type of pointer, direction of increase on scale, and the design of multirevolution instruments. Some of the more important findings are summarized below.

a. Shape of Dial. The five most commonly used dial shapes have been experimentally tested for accuracy of reading by Sleight. All were equated in terms of size and shape of numerals, illumination, and so forth, so that any differences in reading accuracy may be presumed to be primarily due to shape. The shape found to give the fewest reading errors in this test was the open window type of direct reading counter. Mistakes were made in only 0.5 per cent of the readings. The next most accurate dial, although very much inferior to the open window type, was the round or circular type; 10.9 per cent of errors were observed with this display. Following, in order of mistakes, were the semicircular dial, 16.6 per cent; the horizontal, 27.5 per cent; and finally the vertical shape with 35.5 per cent errors.[47]

The marked superiority of the direct reading counter is evident only under conditions of rapid viewing during short exposure. Where the viewing time may be lengthened, the number of errors observed in the other types of dials would be very substantially reduced. Also, for check reading in a group of instruments (see page 87) the moving pointer type of display is definitely superior.

b. Size of Dial. The optimum size of the dial is, of course, related to the viewing distance. For a distance of 30 inches between the display and the eyes of the operator, it has been found that a dial 3 inches in diameter can be read faster and with fewer errors than dials of smaller size. The diameter must be increased for distances above 30 inches and decreased for those below 30 inches.[48,49] An additional variable, however, is the number of scale markings or indices that must be used. Table 5 shows the minimum dial diameters under varying conditions. No dial should be less than 1 inch in diameter regardless of the circumstances.[50]

c. Scale Markings and Numberings. The ease of quantitative dial reading is significantly affected by scale markings and numberings. The common practice of making the numbered division marks longer than the halfway marks is good. For rapid readings, the fewer the marks the better. When accuracy is desired as

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[47] R. A. Sleight. The effect of instrument dial shape on legibility, *J. Applied Psychol.*, **32**, 170–188 (1948).

[48] W. F. Grether, The design of instruments for ease of reading. Paper presented before the Soc. Automotive Engrs. National Aeronautic and Air Transport Meeting, April, 1948.

[49] W. E. Kappauf and W. M. Smith, Design of instrument scales for maximum legibility: II. A preliminary experiment on dial size and graduation, *Memorandum Rept. No. MCREXD-694-IN*, USAF, Air Materiel Command, July 12, 1948.

[50] W. E. Woodson, *Human Engineering Guide for Equipment Designers*, University of California Press, Berkeley, 1954.

TABLE 5
Minimum Dial Diameters[50]
(In inches)

Number of scale markings	Minimum dial diameter for a viewing distance of	
	20 inches	36 inches
38	1	1
50	1	1.28
70	1	1.79
100	1.43	2.57
150	2.14	3.86
200	2.86	5.14
300	4.29	7.71

well as speed, the numbering and division markings should be in the decimal system. If the numbers increase by 10's or 100's, there should be division marks to make the smallest division equal to 1 or 10.[51,52] If accuracy in interpolating between scale markings is important, a large number of markings would be recommended, but a great number of graduation marks produces a cluttered appearance and is likely to cause gross errors (see Figure 8). Scales with number intervals of five with four divisions between numbered graduation marks are poorly designed, though they can be seen on many machines. Consistency of marking and numbering should apply to all dials that must be used consecutively by the same operator. On the basis of present knowledge, at least 1/2 inch linear distance between the numbered division marks is recommended for dials viewed at 30 inches. The height

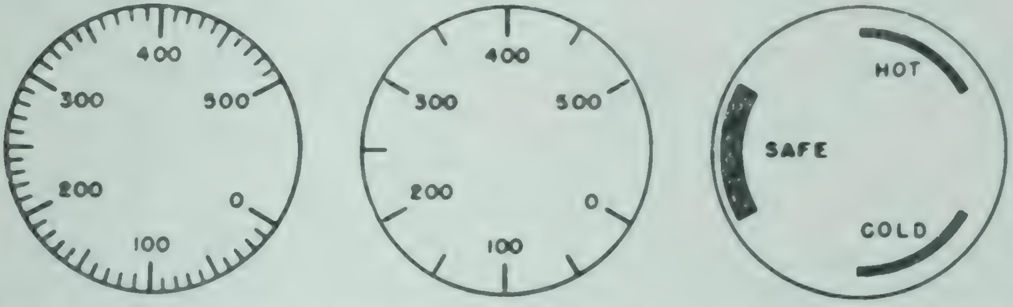

Figure 8. Scale markings. A scale should never have more markings or finer subdivisions than are needed to fulfill its function. A temperature scale such as the one at the left above could be replaced by the one in the center if only approximate quantitative readings were necessary. The scale at the right would be preferable if the safe operating range was all that was desired. As a general rule the fewest reading errors are made with dials having the fewest markings. (From Baker and Grether.[46])

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[51] W. R. Garner and J. W. Gebhard, Machine dials and scales, *Machine Design*, **21**, No. 8, 98–104 (1949).

[52] M. D. Vernon, Scale and dial reading, *Rept. No. 49*, Med. Research Council Unit in Applied Psychol., Cambridge University, England, June, 1946.

of the numerals or markings at various viewing distances is shown in Table 6. The proportions, or height to width ratio of the numerals or letters, should be about 3:2 on dials and 1:1 on direct reading counters.[50]

TABLE 6

Height of Characters and Markings for Dial Design[50]

Viewing distance	Character height (in.)	Marking height (in.)		
		Major	Intermediate	Minor
1 ft. 8 in. or less	.09	.22	.16	.09
1 ft. 8 in.–3 ft.	.17	.40	.28	.17
3–6 ft.	.34	.78	.56	.34
6–12 ft.	.68	1.57	1.12	.68
12–20 ft.	1.13	2.63	1.87	1.13

Since most people expect the values of a scale to increase in magnitude when the pointer turns clockwise, this relation should be incorporated into the original display design if feasible.[53] Otherwise, one can expect "reversal" errors to occur; for example, on a counterclockwise dial if the pointer is on the graduation 21 when graduation 20 is numbered, the worker may read 19 instead of 21.

d. Pointer Design. Experimental research on this topic, although limited, indicates that pointer width is a relatively unimportant consideration: in one instance a reduction from $^3/_{32}$ to $^1/_{32}$ inch caused no loss of legibility. Length, however, is important. Reading errors will increase if the tip of the pointer is more than $^1/_2$ inch from the scale markings. Nor should the tip extend beyond the edge of the outer scale. In general, the whole pointer, rather than only the pointer tip, should be of a contrasting color to the dial.[54] In those jobs in which a worker is required to move a control in co-ordination with the pointer on a visual indicator, the control movement should always be in the same direction as the pointer if possible (see the discussion of "Direction of Movement" on page 100).

e. Multirevolution Instruments. These displays consist of two or more pointers on a single dial face. A watch or clock would be a simple example of an instrument of this type. A single reading thus requires an understanding of the locations and interrelationships of all the pointers. One advantage of this type of instrument seems to be that a large range of values can be compressed into a small physical space. Nevertheless, the numerous reading errors found to be associated with these instruments makes their replacement desirable whenever possible.[24,71] Altimeters are a complex type of multirevolution instrument with a high incidence of reading errors.

[53] J. M. Christensen, The effect of the staircase scale on dial reading accuracy, *Memorandum Rept. No. MCREXD-694-1P,* Air Materiel Command, USAF, October 1, 1948.

[54] P. M. Fitts, Psychological aspects of equipment design, *Tech. Rept. No. 5829,* Air Materiel Command, USAF, August, 1949.

B. OTHER SENSORY DISPLAYS

Although much of the information that a worker obtains is visual in nature, displays may involve other types of sensory stimulation. For example, the behavior of a worker may depend on, and be controlled by, auditory cues, either spoken words (as in a communication network) or mere sound stimuli (such as the noise made by a motor at different speeds). The use of different knob shapes and sizes on levers and switches may constitute a "tactual display." Skilled machinists often refer to the "feel" of their controls. The use of these sounds, shapes, and built-in "feels" on controls should thus be considered as auxiliary ways of insuring that the worker receives all the information he needs. Some of the highlights of what is known about the average worker's capabilities in these sensory fields are discussed below.

1. *Auditory Displays*

Auditory displays may be used effectively as warning or information signals to the worker, thus relieving his visual senses of additional responsibilities. To be most effective, of course, such an auditory information system must be employed in the sound range where the human ear is most sensitive. This applies with respect to the frequency, intensity, and duration of the sound.

The ability of the human ear to detect a change in the frequency of a sound increases with the pitch from a very low value, and then lessens for extremely high tones. The greatest pitch sensitivity is found for tones (of moderate loudness) whose frequency is between 400 and 800 cycles per second. This is the range that should be utilized for auditory information. Intensity discrimination is also poor at low frequencies when the sounds are faint. Under such conditions, the greatest sensitivity to a loudness change is at about 2000 cycles per second. For moderately loud tones (that is, about 40 decibels), however, a normal ear is equally sensitive to loudness changes at all frequencies.[24,71]

To avoid continuous tones, which might become distracting or annoying, auditory cues should be as short as possible. However, they must be sufficiently long to afford the opportunity for adequate pitch and loudness discrimination. The best evidence indicates that both frequency and intensity may be discriminated from durations as short as 20 to 40 thousandths of a second.

2. *Tactual Displays*

Although the tactual sense of form and size is greatly inferior to that of the visual sense, it is nevertheless possible to code equipment knobs in this respect in order to reduce errors in control operation.[55] The use of knobs of various shapes reinforces visual information and assists in avoiding accidental movements when controls must be selected and used without the aid of vision. Shape coding is particularly useful in situations where a specific control is located in different positions in different situations. The "habit interference" that is experienced in these circumstances can be alleviated by this method of coding. A considerable knowledge now exists concerning the shapes that are maximally discernible.[56] These are illustrated in Figure 9. During blindfold tests conducted by the Air Force, it was found that these shapes were the most easily distinguishable, caused the least hesitation and the fewest mistaken identifications.

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[55] P. M. Fitts, Engineering psychology and equipment design, in S. S. Stevens, ed., *Handbook of Experimental Psychology*. Wiley, New York, 1951, pp. 1287–1340.

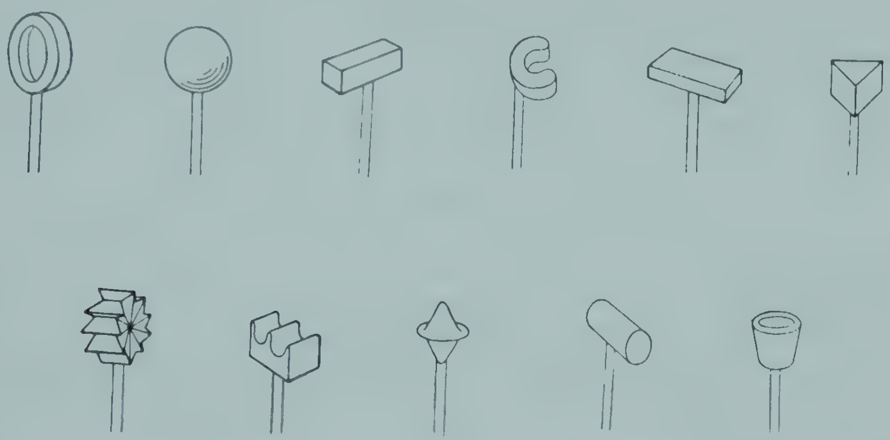

Figure 9. Eleven shapes found most suitable for the coding of control knobs. During experimental tests errors of identification of the knobs in this group were either absent or extremely rare. (After Jenkins[57] and Chapanis *et al.*[24])

3. Kinesthetic Displays

Resistance to movement may also give the operator of a control a cue as to the extent of its activation and thus may be considered as a form of display. There is only limited knowledge concerning kinesthesis (muscle sense) so only tentative recommendations can be given. It is known that people tend to overestimate small pressures and underestimate large pressures. We also know that arm and leg pressures become more accurate and consistent after a certain small force is already exerted. In order to provide as many cues as possible, the range in resistance of the control should extend from this small force up to an amount that will not cause fatigue when pressure must be maintained for a prolonged period.

C. CONTROLS

Industrial workers are sometimes required to perform repetitive tasks; to work at high rates of speed; to reach for, locate, and operate controls without the aid of vision; to make sudden or corrective responses; or to operate over long periods of time without undue decrement of performance. Under these and other adverse conditions, it is important that the equipment be designed so that the operators can continue to control it accurately, rapidly, and safely. When accidents can be traced to inaccurate or careless operation of equipment, it occasionally is found that the design of the equipment itself contributed to the accident. Had the controls been so placed that rapid and more accurate judgments and movements could have been made, many of these accidents would not have occurred. Design and production engineers must, therefore, consider not only the physical tolerances and speed that the machine can achieve and the appearance, cost, and ease of production of the apparatus, but also the tasks that the operator is to perform and his abilities and limitations in performing these tasks. Several experimental findings and principles concerning the design of controls are available and should be taken into consideration when designing equipment in order to reduce operator errors and to make speed of operation easier to maintain.[57]

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[56] W. O. Jenkins, "The Tactual Discrimination of Shapes for Coding Aircraft-Type Controls," in P. M. Fitts, ed., *Psychological Research in Equipment Design*, *Rept.* No. **19**, USAAF Aviation Psychology Program, U. S. Government Printing Office, Washington, 1947, Ch. 14.

1. *Biomechanical Factors Influencing Control Operations*

a. Range of Body Movements. Basic data on the range of motion of the various parts of the human body and the forces that can be applied in different body positions are indispensable for an understanding of control design. Although it is true that the full range of joint motions or the full force of a particular movement is not usually required in the operation of controls, these data establish

TABLE 7

Amplitude of Movement at Various Joints of Adult Males[58]

(In angular degrees)

Part moved and movement	Side	Mean	S.D.	P.E. est.
Head (relative to trunk)				
Flexion (ventral)		59.8	11.7	.54
Flexion (dorsal)		61.2	26.8	.70
Flexion (lateral)	R	39.4	6.0	.45
“ “	L	42.9	7.7	
Rotation	R	77.2	16.1	.63
“	L	79.8	12.8	
Arm (at shoulder joint)				
Flexion (forward)	R	179.0	7.2	.45
“ “	L	179.9	6.3	

[57] J. H. Ely, R. M. Thomson, and J. Orlansky, "Design of Controls," in *Joint Services Human Engineering Guide to Equipment Design*, Wright-Patterson Air Force Base, Ohio, 1956, Ch. VI.

[58] A. D. Glanville and G. Kreezer, The maximum amplitude and velocity of joint movements in normal male adults, *Human Biology*, **9**, 197–211 (1937).

Table 7 (continued)

Part moved and movement	Side	Mean	S.D.	P.E. est.
Extension (backward)	R	55.2	10.1	.45
“ “	L	60.0	12.4	
Abduction	R	129.3	11.7	.60
“	L	130.3	11.2	
Internal rotation	R	94.1	22.1	.59
“ “	L	100.0	16.3	
External rotation	R	82.7	10.0	.55
“ “	L	83.5	16.2	
Forearm (at elbow joint)				
Flexion	R	138.3	8.5	.47
“	L	144.2	8.9	
Pronation	R	91.1	25.8	.94
“	L	93.0	20.7	
Supination	R	99.4	11.0	.88
“	L	100.6	10.8	
Hand (at wrist joint)				
Flexion (palmar)	R	95.0	10.6	.66
“ “	L	90.0	9.8	
Extension (dorsal)	R	54.1	15.2	.61
“ “	L	65.7	12.6	
Abduction (radial flexion)	R	27.1	7.1	.35
“ “ “	L	31.1	8.4	
Adduction (ulnar flexion)	R	66.1	8.1	.65
“ “ “	L	66.1	8.8	
Thigh (at hip joint)				
Flexion (foreward)	R	97.8	17.0	.63
“ “	L	105.6	8.3	
Extension (backward)	R	48.4	12.9	.66
“ “	L	42.4	9.9	
Abduction	R	70.1	17.0	.74
“	L	71.7	14.1	
Internal rotation	R	60.6	15.2	.59
“ “	L	66.3	13.5	
External rotation	R	37.0	6.6	.60
“ “	L	30.4	8.3	
Leg (at knee joint)				
Flexion	R	126.6	6.7	.53
“	L	123.7	6.7	
Foot (at ankle joint)				
Flexion (plantar)	R	28.2	7.4	.74
“ “	L	26.2	8.9	
Flexion (dorsal)	R	36.8	6.6	.45
“ “	L	39.5	8.3	

limits that engineering specifications should never exceed. The ranges of 24 different voluntary bodily movements of the head, upper arm, forearm, hand, thigh, lower leg, and foot are presented in Table 7. The movements are defined in terms of angular degrees for the mean, the standard deviation of the distribution, and the probable error of the mean. All measurements in this table were made by Glanville and Kreezer on a group of 10 subjects.[58]

b. Forces Exertable in Various Body Positions. The positions of the different parts of the body from which the maximum forces can be exerted have been determined by Reijs by means of a dynamometer measuring changes in muscular power during movements. His data may be summarized as follows:

The foot can exert its maximum power in a plantarflexion (or downward) movement when the angle of the ankle joint is about 78°; as the angle increases, the power decreases. For the hand, palmarflexion is a more powerful movement than is dorsiflexion, the average power ratio approximating 10:6 with the maximum for palmarflexion at a wrist angle of about 156° and for dorsiflexion at about 168°.

In the abduction of the leg (movement out from the body) the power drops sharply as the angle of the leg increases from 0 to 50°. In adduction, or movement towards the body, the power is greatest at a position of 32 to 48° and drops slightly as the angle decreases. For the arm, adduction is a more powerful movement than is abduction. The former is greatest between 34 and 68°, while the latter is lowest between these same figures. Flexion of the arm at the shoulder gives greater force than does extension, having its maximum between 68 and 102°. Extension power is greatest at 102°.

Trunk lifting power also was investigated and was found to be least when the trunk is nearly horizontal. There is a consistent increase as the trunk becomes more erect.[59]

c. Rate and Accuracy of Body Movements. When linear body movements are made as rapidly and accurately as possible, both the average and the maximum velocities of movement increase as the length of the movement increases (at least up to 16 inches, the maximum distance studied). Variability in accuracy and speed also increases with the length of the movement.[60] The percentage of error in the accuracy of movements is greatest at short distances and decreases as the distance increases. There is, however, a slight tendency to overreach at short distances and underreach at longer distances. It was noted that the accuracy with which a movement can be stopped at a desired point is not greatly influenced by the distance from the body at which the stop is attempted as long as the length

[59] J. H. O. Reijs. Über die Veränderung der Kraft während der Bewegung. *Pflügers Arch. ges. Physiol.*, **191**, 234–357 (1921).

[60] A. T. Slater-Hammel and J. S. Brown. Discrete movements in the horizontal plane as a function of their length and direction. *Rept. No. 2 on Project 2.* Contract N5ori-57, Special Devices Center, October, 1947.

of movement is constant.[61] For subjects who are trying for accuracy as well as speed in making movements confined to specific limits the mean maximum speeds were found to be 33, 96, and 242 cm. per second for distances of 2.5, 10, and 40 cm., respectively.[62] Right-to-left movements with the right hand are slightly faster than are left-to-right movements. The time to complete movements with the preferred hand is a little less than for two-hand movements, although no differences exist in accuracy.[63]

In studying hand-motion speeds for an industrial task where accuracy was desirable and movement distance was confined, Barnes found somewhat similar rates: 85, 160, and 221 cm. per second for 20.3, 40.6, and 60.9 cm., respectively.[64] These data would indicate that maximum speed will probably not be above 300 cm. per second if the movements are limited to distances of less than about 60 cm. and if accuracy in stopping is required. However, if movements are unrestricted in extent and accuracy but speed is stressed, the rate may well exceed 600 cm. per second.

For winding-type controls the maximum speed at which operators can turn handwheels and still match pointers in a continuous task appears to be about 200 to 250 r.p.m., although large-size handwheels, increases in friction, inconvenient positioning, and awkward hand grip will all tend to lower this maximum speed. Although there is an optimal speed band for each situation within which minimum error occurs, a speed of 180 r.p.m. may be given as a general optimal figure representing many different conditions.[65]

d. Accuracy of Operation with One or Two Hands. No important difference between the reaction time of the hands has been observed.[66] However, among right-handed people the right hand appeared tc be superior to the left in performing tasks where the criterion is strength. The preferred hand is also superior to the nonpreferred hand in tasks requiring continuous, accurate control.[67] The use of both hands for a continuous control task is better than a one-hand control (preferred or nonpreferred hand) in certain cases where accuracy is the criterion, but this difference can probably be minimized by changes in the equipment or in the manipulative techniques used in operating the equipment. Although the evaluation of one- and two-handed controls depends on the specific type being studied, performance with a two-hand control is generally superior to that with a one-hand control, both with and without frictional load.[68,69] The double handcrank has advantages where the load is appreciable and where the steadying effect from both hands on the wheel is desirable, such as under conditions of unsteady footing. It has disadvantages in that it must be mounted almost directly in front of the operator at an appropriate height, whereas the single handwheel can be operated easily within a wide range of positions.

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[61] J. S. Brown and E. B. Knauft, Positioning reactions of uniform length executed at various distances from the body, *Rept. No. 4 on Project 2,* Contract N5ori-57, July, 1948.

[62] J. S. Brown and A. T. Slater-Hammel, The effect of speed-up instructions upon the performance of discrete movements in the horizontal plane, *Rept. No. 3 on Project 2,* Contract N5ori-57, January, 1948.

[63] J. S. Brown, A. T. Slater-Hammel, and E. A. Bilodeau, Characteristics of discrete movements in the horizontal plane when executed with one and with two hands, *Rept. No. 5 on Project 2,* Contract N5ori-57, August, 1948.

[64] R. M. Barnes, *Motion and Time Study.* Wiley, New York, 1949.

[65] The Foxboro Company, Foxboro, Mass., Handwheel speed and accuracy of tracking, *OSRD Rept. No. 3452,* 1943.

[66] R. S. Woodworth, *Experimental Psychology.* Holt, New York, 1938.

[67] D. C. Ellson and D. R. Craig, A comparison of one-handed and two-handed tracking, *Memorandum Rept. No. MCREXD-694-2M,* Air Materiel Command, USAF, n.d.

Other than the two-handed crank, a single crank mounted on a transverse axis was found to be most efficient for continuous-control tasks where accuracy over a period of time was necessary.[69,70] This was true particularly where a load had to be overcome. Reciprocating hand and arm movements, in a horizontal plane, are generally smoother, less fatiguing, and more accurate than are vertical movements. Furthermore, movements outward from the middle of the body in any direction are usually smoother, less tiring, and more accurate than movements inward.

e. *Handedness and Hand Strength.* The percentage of left-handed and ambidextrous people always increases when dextrality is determined by objective tests rather than subjective judgments. The latter are extremely inaccurate and should be avoided. As an example, schoolteachers reporting on 225,000 pupils from grades 1 through 12 found that a total of 8.2 per cent of this population was left-handed. However, when 10 types of gross muscular reaction were tested on 190 subjects, 21 per cent proved to be left-handed (18 per cent male and 23 per cent female). On 4 specific motor tests, with and without vision, given to 100 subjects, this percentage rose to 34 per cent male and 38 per cent female with between 1 and 2 per cent ambidextrous.[71] It has been convincingly demonstrated that handedness is a continuous variable and not an all-or-nothing attribute. The dextrality index, or left-hand strength expressed as a percentage of the right-hand, of 360 civilian drivers was 93 per cent for dynamometer hand grip and 92 per cent for repetitive squeezes to exhaustion.

Hand strength, measured by dynamometer, showed 161 Naval enlisted men to have a maximum grip of 119 pounds ± a S.D. of 14 pounds.[72] A group of 350

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[68] D. C. Ellson and D. R. Craig. A comparison of a two-handed and several one-handed control techniques in a tracking task, *Memorandum Rept. No. MCREXD-694-2L*, Air Materiel Command, USAF, n.d.

[69] The Foxboro Company, Foxboro, Mass., Relative accuracy of handwheel tracking with one and both hands, *OSRD Report No. 3455*.

[70] The Foxboro Company, Foxboro, Mass., A supplementary study of factors determining accuracy of tracking by means of handwheel controls, *OSRD Report No. 3452*, December, 1942.

[71] Handbook of human engineering data for design engineers, Tuft's College Institute for Applied Experimental Psychology, *Tech. Rept. SDC 199-1-1*, NavExos P-643, Special Devices Center, Office of Naval Research, Dept. of the Navy, 1949.

[72] M. B. Fisher and J. E. Birren. Standardization of a test of hand strength, *Research Project X-233, Report No. 5*, Naval Medical Research Institute, National Naval Medical Center, April, 1945.

civilian drivers measured by the Harvard School of Public Health gave a maximum grip of 124 pounds with the right hand and 115 pounds with the left hand. For 200 university men the maximum strength of the right hand was 108 ± 21 pounds and of the left hand, 95 ± 18 pounds. During the one-minute period that this test was given the maximum strength was quickly obtained and thereafter there was a gradual but irregular falling off in strength.[73]

Measurements of hand strength on a group of 552 male, manual, industrial workers showed the maximum hand strength in the middle twenties, with a continuous decline thereafter. At the age of 60 this decline amounted to 20.4 pounds, or 16.5 per cent from the maximum. Maximum strength was at the age range of 23 to 27 years.[74] The findings agree with other data, which show that strength increases up to the middle or late twenties and declines continuously thereafter. In most studies the rate of decline increases with age.

2. Principles of Control Design

a. Location. In the placement of controls in the operator's workplace, consideration should be given not only to the range of functional arm reach, as discussed above, but also to the frequency with which each control is to be used, the type of control and manner in which it is to be operated (push button, lever, crank, knob, and so forth), the forces involved, accuracy and speed required, the sequence in which it is to be used with respect to other controls, and the conditions under which it is to be used—especially its importance in emergencies. Some machine operators, for example, must occasionally reach for controls without removing their eyes from their work. Sometimes controls are reached for blindly even though visual cues could be used. Studies have been conducted to determine the accuracy and speed with which individuals are able to locate positions at arm's length within the area easily reached from a seated position without the aid of visual cues. In one study, 50 men were tested for the accuracy with which they could reach 20 different targets mounted in different areas around them at distances of 30 inches from the mid-point of the shoulders. Visual references were available to them, but they could not see the targets or their own bodies. It was found that accuracy was best for forward areas. For side areas, accuracy was best for points lower than the level of the shoulders and for points nearer the front. People tend to reach too low for points above the shoulder level, too high for points below the shoulder level, and too far to the rear for points located on either side.[75] Results of the study indicate that forward areas between the shoulder level and the waistline probably are ideal for the location of controls. Controls placed above the shoulder level might not only be located inaccurately without visual aid but might also result in fatigue if operated frequently. Placement at about elbow height is probably best for those controls that are to be operated continuously.

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[73] W. W. Tuttle, C. D. Janney, and C. W. Thompson, Relation of maximum grip strength to grip strength endurance, *J. Appl. Physiol.*, **2**, 663–670 (1950).

[74] M. B. Fisher and J. E. Birren, Age and hand strength, *Research Project X-293, Report No. 7*, Naval Medical Research Institute, National Naval Medical Center, December, 1945.

[75] P. M. Fitts, "A Study of Location Discrimination Ability," in P. M. Fitts, ed., *Psychological Research in Equipment Design, Rept. No. 19,* USAAF Aviation Psychology Program. U. S. Government Printing Office, Washington, 1947, Ch. 15.

Point of origin, reaching distance, and terminal point all influence the accuracy with which movements can be made.[76] In general, it appears that controls in forward areas should be located at least 6 to 8 inches apart if reasonable certainty of not grasping the wrong control when "reaching blind" is desired. Work areas should be "cleared up" so that unnecessary objects or controls, or moving or dangerous parts, are eliminated. Such a program could result in a reduction in the number of cases of inadvertent operation of controls, the erroneous operation of one control for another, the inability to locate a control quickly enough due to confusion, or accidental entanglements with the machinery.

b. Direction of Movement. Analysis of errors has indicated the importance of taking into account the relationships between the movement of the display desired (whether a pointer, a drillpress head, or a crane boom) and the direction of motion required by the control to produce that movement. This is particularly true when sudden and discrete movements of the controls are required. It is important that a control handle should move so that the resulting display movement is in the "expected" direction in order to minimize the possibility of accidental movement of the control in the wrong direction (see Figure 10).[2]

In order to define these "expected" directions, it was observed how operators moved a rotary control in order to center a linear display when different spatial arrangements existed between the display and the control.[77] Operators consistently responded as though they expected the movement of the indicator to be in the same direction as that portion of the knob adjacent to the indicator. It was found that arrangements in which both the control and the indicator were in the same perpendicular plane facing the operator brought about more consistent responses than arrangements in which control and indicator were not in the same plane.

Other studies have confirmed the above finding that when individual responses are required, fewer errors occur if the movement of a control lever produces a response in the "expected" direction.[78,79] In other words, fewer errors are made when an upward movement of the control produces an upward movement of the display and a downward movement of the control produces a downward movement of the display. The second best relationship was found to be a forward movement of the control to move the display up with a backward movement to move the display down. Display-control relationships have also been found to result in fewer errors

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[76] P. M. Fitts and C. Crannell, Location discrimination: II. Effect of twelve days of practice on the accuracy of reaching movements to twenty-four different areas, *Memorandum Rept. No. MCREXD-694-41,* Air Materiel Command, USAF, n.d.

[77] M. J. Warrick, "Direction of Movement in the Use of Control Knobs to Position Visual Indicators," in P. M. Fitts, ed., *Psychological Research on Equipment Design, Rept. No. 19,* USAAF Aviation Psychology Program. U. S. Government Printing Office, Washington, 1947, Ch. 9.

[78] M. A. Vince, *Direction of Movement of Machine Controls.* Flying Personnel Research Committee, Med. Research Council Unit in Applied Psychol., Cambridge University, England, 1946.

[79] M. J. Warrick and W. F. Grether, The effect of pointer alignment on check reading of engine instrument panels, *Memorandum Rept. No. MCREXD-694-17,* Air Materiel Command, USAF, June 4, 1948.

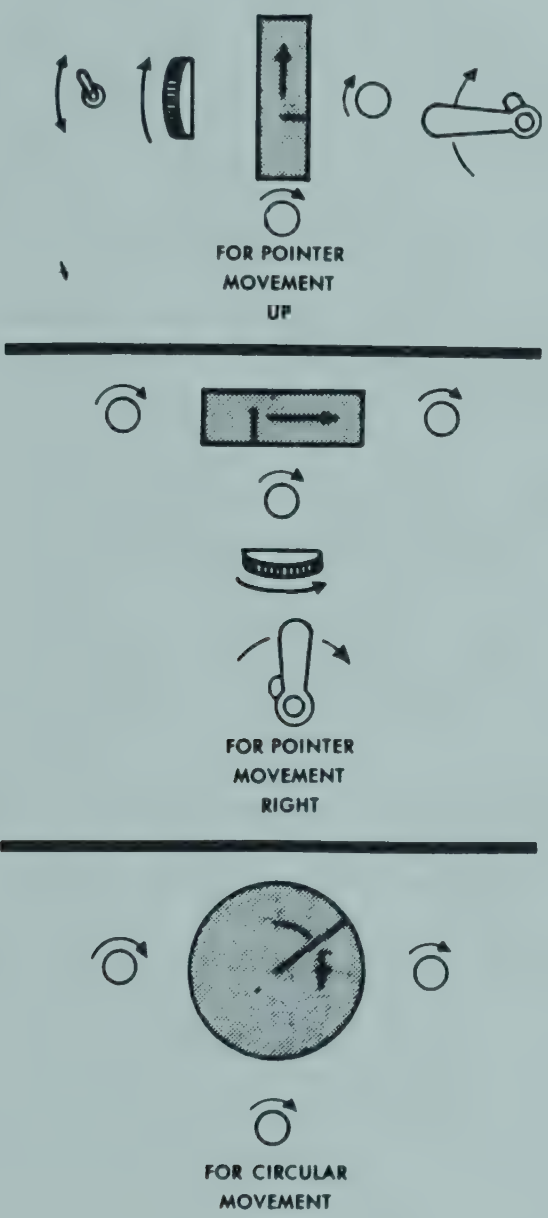

Figure 10. Expected relationships between controls and displays. The proper direction of movement for knobs, cranks, and toggle switches is indicated above for corresponding pointer movements upward, to the right, and in a circular direction. (From Woodson.[50])

in a discontinuous task carried on with the right hand when the left hand was performing a fairly difficult but dissimilar and continuous task.[80]

"Expected" relationships probably originate in the previous experiences of individuals rather than in any anatomical organization. Even though the "unexpected" relationships may be learned quickly, in many cases the great amount of previous contrary experience probably contributes toward the rapid forgetting of these learned relationships. Certainly, the use of other controls with confusing similarities and differences between the particular "unexpected" display-control relationships would be likely to lead to errors in the operation of the latter. In addition, even though an operator has learned to make correct, "unexpected," display-control responses, he is very likely to respond in the way most natural to him when an emergency arises, and his response will therefore be in error. This, of course, will vary with the level of learning of the "unexpected" response.

In one panel arrangement, subjects first turned a knob in order to center a light in a semicircular display, and then turned a second knob in order to center a light in another semicircular display. This alternation between panels was continued for a series of responses. Time and error scores were not large when a clockwise control movement produced a clockwise indicator light movement on both panels, nor were they large when a counterclockwise control movement produced a counterclockwise indicator light movement on both. However, when a clockwise-clockwise relationship existed on one panel, and a clockwise-counterclockwise relationship on the second, time and error scores increased greatly for both.[81] Such data clearly indicate the importance of having standard display-control relationships on all equipment in order to avoid errors in rapid responses.

If the best arrangements and relationships are employed when controls are designed for situations in which visual displays must be responded to rapidly and accurately, speed of response will be increased, learning of the control task will probably be facilitated, and incorrect responses will be less likely to occur, particularly when the operator is working under conditions of boredom, fatigue, or emergency. If compromises must be made in the direction-of-motion relationships between display and controls, it is probably more important that all controls on the panel have the same direction-of-motion relation to the displays even though they may not be the most "expected" relationship. Another alternative is to make the dial having an "unexpected" relationship to a control a different type of display than the others (for example, a linear type if the others are circular), so that its differentiation is obvious.

In tasks where only one control is used continuously, the problem of the direction-of-motion relationship does not appear to be significantly important unless the task is of short duration, when it more nearly approaches the discrete type of response situation. Even here, since these controls are likely to be operated in conjunction with others, it is better that "expected" relationships be used if possible.[2,24]

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[80] R. E. Jones. A survey of pilot preferences regarding knob shapes to be used in coding aircraft controls. *Memorandum Rept. No. MCREXD-694-4E*. Air Materiel Command, USAF, October 1, 1947.

[81] M. J. Warrick. Effect of motion relationships of speed of positioning visual indicators by rotary control knobs. *Tech. Rept. No. 5812*. Air Materiel Command, USAF, October, 1949.

c. Shape. The most efficient shapes for hand controls were determined by testing several types of knobs subjectively and objectively on the basis of maximum force applied, arc through which the knob turned, and time required for grasping and releasing. A two-pointed (cigar) shape and a four-pointed star gave the highest mechanical advantage and were also favored by the subjects. Of the two, the four-pointed knob is superior in that it is easier to obtain a new grip on this form when a partial turn has been made. Circular controls and three-, five-, six-, and eight-pointed controls were much less satisfactory.[82]

The use of different shapes has also been found to reduce the time required for the accurate operation of a series of controls. For instance, if the positions of controls are changed after individuals have learned one set of operations, the time required to perform accurately a series of tasks with the controls is increased.[57] However, if the control handles are coded with regard to shape, the detrimental effect of shifting the location of controls is minimized even when visual cues are reduced. If standardized, this type of coding would be of great value where new operators are learning to operate a machine with a large bank of controls, and it would be of particular value when a trained operator, or perhaps an older operator, shifts from one machine to another where the controls are in a different position. He could verify his choice of controls and avoid errors even though he might tend to reach for and operate the controls through force of habit without the aid of vision (see "Tactual Displays" on page 92).[2] Coding may also be achieved by the use of specific colors for certain controls or types of controls. Color coding may be used independently of, or in conjunction with, shape coding.

d. Size. In controls requiring the exertion of negligible force, such as the setting of indicator pointers, the diameter of the knob has little influence on the time required to make the setting provided only that it can be conveniently grasped. A knob of about $2^3/_4$ inches in diameter appears to be a favorable size. The use of a crank handle does not aid, and possibly hinders, the speed of adjustment in a task of this type.[83] The same general finding has been reported for knobs used in tuning for maximum signal strength, as where bracketing would be used (moving the control approximately 30° to one side and then to the other, and attempting to halve the distance by feel). For a knob with the axis at right angles to the operator's forearm a diameter of 1 to 2 inches has been found superior. For a knob with axis pointing toward the operator and in line with his forearm, a diameter of 1 to $3^1/_2$ inches is satisfactory.[84]

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[82] A. Wallichs and F. Hulverscheidt, Die Bedienbarkeit von handgriffen Vorrichtungen, *Werkstattstechnik und Werksleiter,* **29,** 193–197 (1935).

[83] W. O. Jenkins and M. B. Connor, Some design factors in making settings on a linear scale, *J. Applied Psychol.,* **3,** 395–409 (1949).

One of the primary determinants of the size of a knob is the torque that is to be exerted upon it. This introduces one exception to the superiority of the four-pointed star shape mentioned above: when small torques are desired (65 to 110 pound-inches), a cylindrical knob 2 inches in diameter is preferable. If it is to be placed facing the operator, a circular knob with a heavy rim should be used since this can be easily grasped with the finger tips instead of the entire hand. To develop a torque between 130 and 175 pound-inches, the diameter should be 4 inches.[82]

In continuous-adjustment tasks involving the use of handwheel controls, the results of tests with two wheels were compared, one with a radius of $2^1/_4$ inches and a second with a radius of $4^1/_2$ inches. Relatively better scores were obtained with the wheel of larger radius at slow speeds, whereas the reverse was true at high speeds. Even a handwheel with an 8-inch radius can be used with slight advantage up to 60 r.p.m., although the maximum rate of turning is lower than with the smaller handwheels. This effect of handwheel size is small, but it appears from these studies that an optimum radius would be about 3 to $4^1/_2$ inches provided the friction is small (2 to 3 pound-inches). With handwheels in this size range, accuracy in use tends to increase with increasing handwheel speeds up to near the human limit of turning speed. Maximum accuracy for different handwheels varies from 140 to 200 r.p.m.[85]

e. Gear Ratio. The optimum gear ratio for tasks in which an operator sets a pointer by turning a knob, such as in radio tuning, is approximately $1^1/_2$ inches of pointer movement for every revolution of the knob.[83,86]

When a lever-type, nonlinear control (variable gear ratio) was tried, it was found that subjects responded as though they expected a linear response to their control movements. In a continuous-control task, no consistent differences in accuracy were found between tracking with linear and nonlinear levers.[78] However, when large discontinuous movements were being made, and the nonlinear relationship had not been explained to the operators, there was a marked advantage in favor of the linear lever. When the nature of the nonlinear lever had been explained and large discontinuous responses were made, the errors were reduced. However, there was little improvement with practice and a difference remained in favor of the linear control.

In continuous-control tasks, low handwheel-gear ratios and high handwheel speeds are advantageous when accuracy is important. This is particularly true for untrained personnel.[65]

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[84] K. J. W. Craik and M. A. Vince. A note on the design and manipulation of instrument knobs. *Rept. 46/252*, Med. Research Council Unit in Applied Psychol., Cambridge University, England, January 14, 1945.

[85] The Foxboro Company, Foxboro, Mass., Inertia, friction and diameter in handwheel tracking. *OSRD Report No. 3454*, 1943.

[86] A. Chapanis. Psychology and the instrument panel, *Scientific American* **188**, 74-82 (1953).

f. Friction and Inertia. With continuous-winding tasks, viscous friction and inertia, as from heavy handwheels or flywheels, seem to have a beneficial effect on accuracy of control. In a lever type of control, however, friction has a negative effect.[87] This advantage of inertia tapers off more rapidly for small-radius handwheels than for large ones because of the force necessary to accelerate loads when using the small-radius controls.[85] Viscous friction and inertia are particularly valuable for accurate control under bumpy conditions or where vibration is present. Friction up to 4 pounds at the handle has been found beneficial, but it does not appear likely that the use of higher values would result in any improvement.[87]

In continuous-control tasks using handcranks, coulomb friction, or "striction," has been found to have a deleterious effect on the smoothness and accuracy of the response. Values up to 7 pounds are increasingly detrimental; higher values are likely to be much more so. This effect is less apparent for high handwheel velocities and heavy handwheels.[85] Although this type of friction is practically always present to some extent in control systems, its reduction is apparently worth while where accurate control is required.

With lever-type controls for continuous-control tasks it is feasible to build into the system a pressure feedback cue that increases with displacement. This cue would supplement the position cue of the control and would probably enable the operator to know the position of his control better and thereby attain more accurate operation. The pressure, however, should not be so great as to interfere with the most rapid movement required in the task. Further, this use of pressure should be limited to situations where the control need not be operated over intervals long enough to result in undue fatigue.[2]

g. A Stable Platform for Operations. The operator of any type of machine or equipment should be able to maintain an upright posture on a stable working platform, whether seated or standing. Deviations from an upright position, such as occur in the bending of the trunk or body or in the extreme movement of an arm or leg, result in the nonproductive use of energy and hence reduce the efficiency of the work. Further, bending or rotating of the head or trunk inevitably alters the visual field so that the view of the area may be modified or reduced. An operator should be able to move freely, shift his weight, and adjust to a more comfortable position whenever he so desires. He should not be required to carry out repeated major body movements for the performance of his task because of deficiencies in design of the work space.

However, some tasks may require fairly extensive body movements. In such cases the worker can, by movement of his trunk, adjust his center of gravity to the position of his base in many different locations. He can also extend his base in any desired direction by shifting the position of a foot. It is necessary, therefore, that a satisfactory area be provided for him to carry out compensatory shifts of his trunk or foot. If operations must be conducted from the standing position and involve such movements as manual adjustments with extended arm reach, or the removal of one foot from the ground to operate controls, suitable hand or foot rests should be provided. These furnish not only an additional point of postural support, but also eliminate unnecessary energy requirements that would otherwise be needed for support of the extended extremity.

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[87] W. E. Hick, Friction in manual controls with special reference to its effect on accuracy of corrective movements in conditions simulating jolting, *Rept. 47/386*, Med. Research Council Unit in Applied Psychol., Cambridge University, England, June 18, 1945.

The lack of a stable platform of operations will force the worker to divide his attention between maintaining his posture against unusual disorienting forces and operating his machine. Further, the additional energy utilized for maintaining balance is nonproductive. In consequence, unstable or slippery footing, inadequate seating, and poor body support all adversely influence control operation, reduce efficiency, contribute to muscular and perhaps mental fatigue, and greatly increase the opportunity for injury.

h. Emergency Controls. An emergency control is generally operated by the worker making the error or having the accident. Hence, it should be placed so that it can be operated by other members of the body than the one likely to become caught or injured in the apparatus. Whether the safety stop should be operated by hand or foot or by either is dependent on the task and on certain other factors involved in rapid control operation. Hand-operated controls have some advantages in that the reaction time of the hands is less than that of the feet. Moreover, if the operator is standing, he may have to shift his weight from one foot to the other in order to manipulate a foot control, thereby adding time to the operation.

If the emergency control is to be operated by the hand, it should be positioned within easy reach by either hand when the operator is at or near the normal workplace or near the area where the injury is likely to occur. The same, of course, is true for a foot-operated control. The control should not have to be used accurately and should require only a small amount of force. Since speed of operation is probably the most important factor in determining the success of an emergency control, any arrangement that can only be operated by one particular limb (such as the right foot) is likely to be unsuccessful.[2]

i. Foot Controls. Human engineering data relating to the design of foot controls are less complete than the comparable data on hand controls. In general, however, the problems encountered in the design of foot controls are relatively less complex. Front-to-back seat adjustability can establish satisfactory access to foot controls for people of varying leg lengths, as mentioned above under "Seating Dimensions." The lateral location of pedals frequently can be more critical, however, especially in vehicular or other types of equipment where frequent use of several pedals is essential both to the operation of the machine and to the safety of the operator. When foot controls are crowded, many operational difficulties are often present, especially with heavier footgear, such as the unintentional application of one pedal while attempting to depress the other, or undue delay in removing the foot from one pedal in order to avoid striking the edge or underside of a second pedal. The optimum lateral spacing will vary widely depending on the size and type of shoes or boots normally used on the job. Clearances should not be made unnecessarily large, however, especially between pedals to be used in rapid sequence, since this may increase application time.

One of the aims of foot-pedal design is to lower the energy demands on the operator. This can be accomplished in part by a lever-arm ratio requiring relatively small amounts of work. The machine layout may sometimes place the leg in unnatural positions or may require the driver to make complex compensatory movements in order to move the foot from one pedal to another, thus resulting in unnecessary fatigue. For this reason there should be no structural interference with the movement of the leg or legs during operation of the controls. In order to avoid unnecessary leg motion, the height of a foot pedal in the rest position should never exceed 10 inches above the floor, 8 inches being preferable. In all cases there should be a reasonably large contact area between the sole of the foot and the pedal in order to prevent slippage, and for pressure of long duration, contact with the whole foot is desirable.[88] However, since the arch of the foot can exert a greater force than the toe, the foot should be applied to the pedal so that the distance from the heel to the pedal axis is about 4 inches.[89] This fact is confirmed by the research of Clark and Weddell, who state that maximum force with minimum fatigue is attained when the bones of the lower leg are in a direct line with the pedal axis. This point of contact is toward the front of the heel. It was found, in addition, that the optimum leg position, of those tested, for exerting maximum pressure without strain was with the thigh horizontal and the knee at a 45° angle from the vertical. If the thigh is elevated from the seat a greater pressure can be exerted. Should adjustability be desirable and feasible in the pedal stalk itself, there are some data to indicate that about $8^1/_2$ inches of adjustability will be necessary in order to accommodate persons (males) of different body size.[90]

3. Standardization of Equipment

One of the major factors that may cause a worker to deviate from the best method of doing a job is the variable nature of the controls and equipment provided for him.[91,92] Frequently the individual is called upon to employ different models of some type of device in order to effect a given end. The arrangement of the controls, the manner in which they are operated, and their "feel" may differ significantly from one model to another. Even though the different models are equally effective in performing a given operation, the difference becomes important because it introduces novelty into a situation where uniformity is needed. In many industrial tasks, it is essential that the worker devote his whole attention to the result and not to the means. A good example is the operation of a motor vehicle through heavy traffic. Here the operator should be devoting his attention to his surrounds and to making judgments relative to distances, directions, and speeds, and not to the manner in which his controls are to be operated.

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[88] H. Koch, Fussbediente Arbeitsmachinen und Ermudung, *Arbeitsschutz,* **3,** 52–59 (1941).

[89] E. A. Muller, Die gunstige Anordung im sitzen betatigter Fuszhebel, *Arbeitsphysiologie,* **9,** 125–127 (1936).

[90] L. G. Clark and G. M. Weddell, The pressure which can be exerted by the foot of a seated operator with the leg in various positions, *R. N. P. 44/153,* Royal Naval Personnel Research Committee, Med. Research Council, Cambridge University, England, 1944.

[91] P. M. Fitts, Psychological requirements in aviation equipment design. *J. Aviation Med.,* **17,** 270–275 (1946).

[92] P. M. Fitts, Psychology and aircraft design. *Mech. Eng.,* **69,** No. 2, 135 (1947).

To be truly effective, equipment, insofar as possible, should be amenable to automatic operation. It should provide the opportunity for the utilization of habitual modes of action. This does not imply that the worker should never change his response as any change in the situation may require. Rather, the fundamental motions he employs should be so stabilized that in moments of stress and decision he should be able to devote himself to solving the problems so suddenly presented and not to the types of movements he is to make. When the worker is called upon to utilize different models of equipment, he must pause and consider the manner in which the particular equipment operates and is thus unable to give his entire attention to the larger problem confronting him. Furthermore, when the worker is confronted with different equipment from time to time, he may never be able to develop appropriate habitual responses because of the constant change. With standardized equipment, the worker can devote his entire attention to the situation confronting him and thereby can anticipate and deal more effectively with whatever hazardous circumstances develop.[2]

IV. Design of the Working Area in Relation to Environmental Variables

The way in which a worker carries out his job is influenced to a large extent by a group of physical variables consisting of temperature, humidity, noise, vibration, and so forth, and any other features especially characteristic of the working environment. The optimum integration of the man with the machine cannot be achieved, in a human engineering sense, unless these physical variables are taken into account in the initial design, or the redesign, of the worker's machines and equipment, as well as the whole of his immediate working area.[93] Many of the variables pertinent to this discussion are given detailed treatment in special chapters of this volume and hence will be treated here only briefly in regard to certain selected aspects.

Much of the research in human tolerances to physical variables has been based upon physiological hazards to man or upon sensory stimulation. However, another important kind of tolerance to consider is what may be called a performance tolerance where some definable impairment in performance serves as a criterion

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[93] R. A. McFarland, *Human Factors in Air Transportation—Occupational Health and Safety*. McGraw-Hill, New York, 1953

One example might be the level of sound intensity at which a worker's co-ordination becomes measurably impaired; a specific feature of a man's behavior is thus examined rather than only possible damage to his ear.

Such tolerances are very significant for industrial safety because they refer to conditions in which an employee's performance may be below par and errors may be prevalent. This point of view takes account of those factors, such as illumination, sound, and temperature, which may have adverse effects upon an operator's performance and which may be controlled through human engineering techniques. An increased error rate is often one result of exceeding an operator's performance tolerances for one or more of these variables. Although there are many studies of the effects of environmental variables upon behavior, much of the information has not been gathered and systematized so as to specify performance tolerances. The best way to prevent accidents through control of the environment is to determine the appropriate tolerances of employees and then to provide working conditions in which these tolerances will not be exceeded. In Figure 11 the

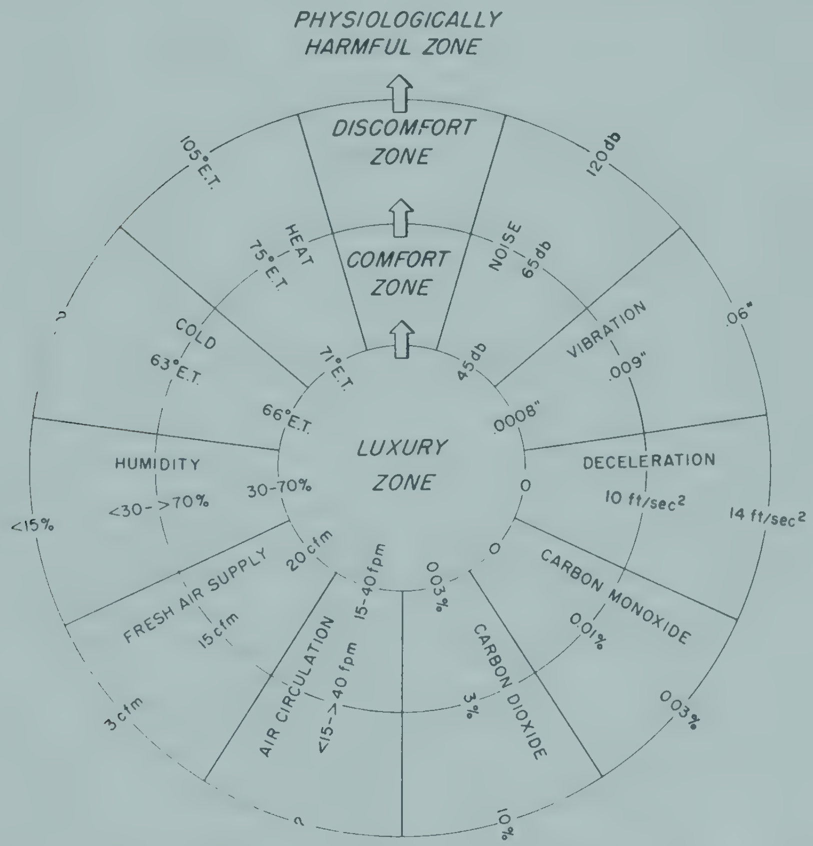

Figure 11. The physical variables of the environment and their influence on comfort, discomfort, and health. These figures were prepared specifically with reference to the operators and passengers of commercial vehicles, but could be applied in a general way to some other types of work. A schematic figure such as this can, of course, give only approximate values since each variable is interdependent with one or more additional factors. (After McFarland.[93])

limits of comfort, discomfort, and physiological harm are indicated for several variables. This chart was prepared specifically with reference to commercial vehicle design and operation but may have some applicability in other industries.

A. TEMPERATURE AND HUMIDITY

In view of the evidence indicating the effect of heat stress on accident rates in various types of work, temperature control for the working area must be considered a necessary part of any program in human engineering. For moderate to heavy manual labor, Vernon, Bedford, and Warner have shown that accident rates among mine workers bear an orderly relation to temperature. Near 60° F. accidents were at a minimum, with two- to threefold increases at temperatures approximating 80° F.[94] In light manual work involving an element of manual dexterity, Osborne and Vernon conducted studies in British munitions factories, that show that both cold and heat stress increase the frequency of accidents in manual operations concerned with shell manufacture.[95] Accidents were at a minimum at 67° F. and increased both above and below this temperature. It is to be assumed that the 35 per cent increase noted at 50° F. is an effect primarily on manual dexterity. The increase with higher temperatures may reasonably be attributed to decrease in general alertness and to increased physiological stress of uncomfortable heat. In skilled work involving minimal physical exertion, Mackworth has shown that during long periods of work, errors increased from an average of 12 per hour to more than 90 per hour as effective temperature was increased from 79 to 97° F.[96] In the sense that errors in skilled acts may be considered accidents, such data are convincing evidence of the deleterious effect of heat stress on human adjustment.

It is thus quite clear that control of the heat loss of workers is important in relation to accident susceptibility. In addition, the provision of a controlled atmospheric environment is a factor in employee morale. In a general sense, the imposition of any stress such as heat or cold will probably produce poorer performance over a long period, which is likely to be characterized by higher accident incidence. To some degree, such a higher accident frequency may reflect both a conscious and an unwitting protest against a subjectively stressful and uncomfortable environment. There are, however, some physiological circumstances of an objective nature that can contribute to an understanding of increased accident susceptibility at elevated temperatures.

At high temperatures, the diversion of a large portion of the heart's output of blood to peripheral areas for cooling purposes reduces the reserve in the circulatory supply to the brain areas responsible for work integration and precision in movement and discrimination, with the attendant possibilities for personal error. The observed effects of high temperatures on accident rates can be tentatively attributed to this factor. Moderate cold stress, though uncomfortable, is usually associated with an alert mental condition. Quite probably the accidents associated with excessively cool conditions are related to chilling of the extremities and a general decline in manual dexterity or, where falls are involved, to a decline in the precision of foot placement.[2]

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[94] H. M. Vernon, T. Bedford, and A. G. Warner. The relation of atmospheric conditions to the working capacity and accident rate of miners, *Indus. Fatigue Research Bd. Rept. No. 39*, London, H. M. Stationery Office, 1927.

[95] E. E. Osborne and H. M. Vernon. Two contributions to the study of accident causation, *Indus. Fatigue Research Bd. Rept. No. 19*, London, H. M. Stationery Office, 1922.

[96] N. H. Mackworth. Effects of heat on wireless operators, *Brit. J. Ind. Med.*, 3, 143 (1946).

The advantages of air conditioning should be seriously considered for all industrial operations carried out for any length of time under conditions of high temperatures, either atmospheric or environmental in origin. The requirements of customer or passenger comfort frequently necessitate air-conditioning equipment in stores, offices, and various forms of transportation. In industry, however, the worker must sometimes perform his job under conditions of moderate to intense heat. The added expense of such air-conditioning equipment must be considered, of course, but only in the light of the attendant increase in the safety, health, efficiency, and morale of the worker. In many industrial operations, the over-all advantages of this equipment could well justify the initial financial outlay. For a complete discussion of the problems involved in work under conditions of excessive temperatures see Chapters VIII and XXI.

B. NOISE AND VIBRATION

If quantitative data can be presented to the engineer in regard to limits of control for noise and vibration, an important contribution could be made to the improvement of efficiency, the lessening of fatigue, and the reduction of the possibility of accidents. Those principles related to noise that are especially important from the standpoint of safety may be summarized as follows. (*1*) Sudden loud sounds tend to speed a worker's movements. This effect is noticeable even when the sound is unrelated to the worker or his task (for example, a foreman's call bell), but it is even more marked when the sound is related to the immediate task (for example, a signal to proceed with the next operation). Although this principle can be used to advantage in some situations, its possible effect upon operator errors must be scrutinized carefully. (*2*) Sudden loud sounds may also tend to disrupt sequences of movements. Photographs of movement sequences often show irregularities for a few seconds after a fairly loud sound. Quantitative specifications for the suddenness or the loudness of these distracting sounds have apparently not been worked out systematically. (*3*) Increased sound levels or added noises may increase error rates at least temporarily; and, conversely, decreased intensity levels or disappearance of sounds may reduce error rates. These effects are likely to be more pronounced when there is a prevailing belief among the workmen that the noise affects their work adversely.[2]

The masking effects of one sound by another have a direct bearing upon the problem of communications among workmen. The principles of masking that are especially important are (*1*) as the intensity level of the disturbing sound is increased, communication by speech becomes progressively more difficult and subject to errors; and (2) strong frequency components near the frequencies of speech sounds are more disruptive than very high or low audible frequency components.[97] Special training in speaking and listening can yield very significant improvements in communications under noisy conditions.[98] For instance, the avoidance of words of low intelligibility in the presence of noise may yield valuable improvements in communications. When workmen must communicate frequently in noisy places, a set of gestures and hand signals often develops spontaneously. However, it should be realized that precise understanding of the signals may well be lacking. They may have been established without any special forethought and may be totally inadequate when certain circumstances involving hazards arise. Wherever hand signals are used, it is advisable to review the system critically with a view to determining the dangers of misunderstanding.[2]

The degree of speech communication possible in the presence of noise of given intensities and frequencies has been determined by Rosenblith, Stevens *et al.*, and should be useful for setting maximum permissible noise levels for certain jobs or areas (see Figure 12). At the 55 decibel level (SC-55) conversation is intelligible at a distance of several feet with a normal voice. At the 65 decibel level, however, communication is difficult, while at 75 decibels communication is marginal.[99] It should be noted that the speech communication level expressed in decibels varies with the frequency, or "pitch," of the sound. At low frequencies a given background noise is less detrimental to communication than it is in higher frequencies. In addition, interrupted noise or discontinuous tones are much more annoying than are steady noises. For a complete discussion of noise and its physiological effects upon man in industry see Chapter XVIII.

Vibration may be frequently linked with noise in many industrial jobs since the two often have common origins. The specific effects are not too well known, although it has been definitely established that vibration adversely influences binocular acuity, especially at frequencies between 25 and 40 and between 60 and 90 cycles per second. This may be due to the attempt of the eyes to follow movements of vibrating instruments or because the eyeball is set into resonance with the vibration. Certain reflex actions of the body may be diminished at some frequencies, while others may be completely depressed at different amplitudes.[24] In addition, it is known that people exposed to vibration for long periods of time frequently complain of headaches, exhaustion, and fatigue. Figure 13 shows the subjective responses as determined by three investigators.[93] Since the human body is quite sensitive to the various types of vibration encountered in some industrial tasks and is usually much less capable of tolerating this vibration than is the structure of the machine or environment, it is essential that operators' physiological limits of tolerance be clearly recognized. However, the reaction to vibration varies at different frequencies and amplitudes. In cases where different vibrations composed of varying frequencies and amplitudes are superimposed, the ones with the higher values should be chosen in determining comfort or safety criteria since these will be the more unpleasant, that is, the higher the frequency the lower the

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[97] S. S. Stevens and H. Davis, *Hearing: Its Psychology and Physiology*. Wiley, New York, 1938.

[98] G. L. Dragert, J. C. Kelley, M. W. Buck, and T. D. Hanley, Training manual for portable interphone trainer, *Special Devices Center Tech. Rept. 104-2-12*, Port Washington, N. Y., n.d.

[99] W. A. Rosenblith, K. N. Stevens, and the Staff of Bolt, Beranek, and Newman. Handbook of acoustic noise control: Volume II. Noise and man. *WADC Tech. Rept. 52-204*, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, 1953.

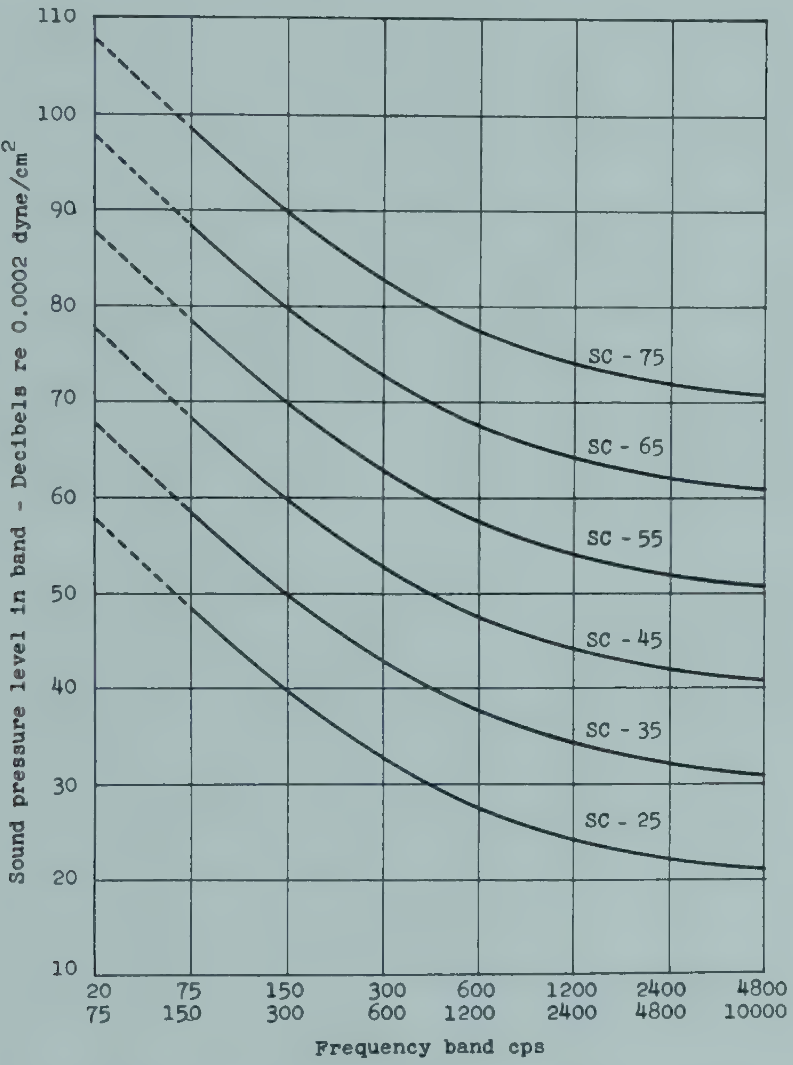

Figure 12. Speech communication criteria (SC). If the sound pressure levels of the environment do not exceed the SC-45 curve at the various frequency bands, relaxed conversation will be possible with a normal voice at a distance of 10 feet. At the SC-55 level communication is possible with a normal voice at 3 feet, with a raised voice at 6 feet, and with a very loud voice at 12 feet. For SC-65 a raised voice is necessary at 2 feet, and a very loud voice at 4 feet. At SC-75 communication is minimal, requiring a very loud voice at 1 foot and shouting at 2 to 3 feet. (After Rosenblith, Stevens *et al.*[99])

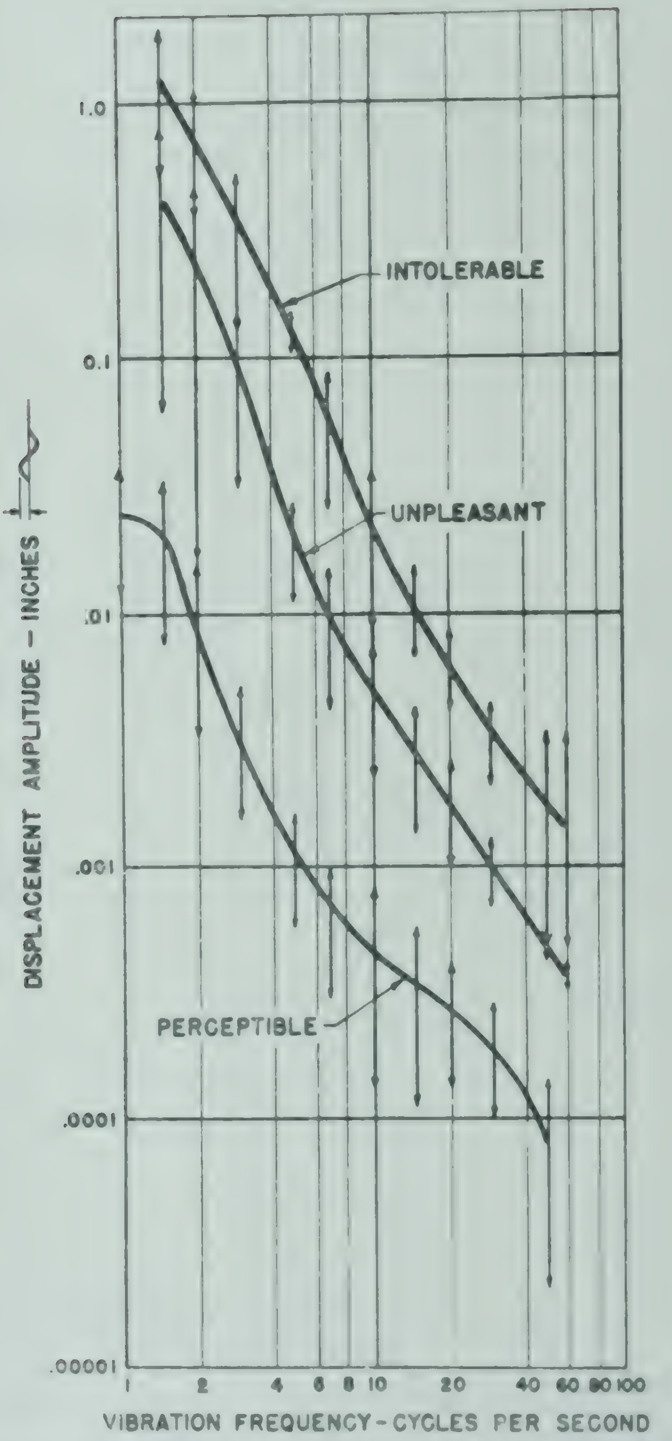

Figure 13. Subjective responses to vibratory motion. The chart is based on the averaged values of various investigators and is valid for exposures up to a few minutes. The vertical arrows represent one standard deviation above and below the means. (From Goldman.[300])

amplitude must be to maintain a given level of comfort, and vice versa. By referring to Figure 13 limits may be determined for any given amplitude or frequency.[100] Ideally, of course, both should be reduced as much as possible.

V. Summary and Conclusions

The objective of this chapter is to indicate methods of controlling the human factors involved in industrial accidents through the application of human engineering principles to problems of equipment design. It is emphasized that closer collaboration should be developed and maintained between the medical and biological scientist and the design and safety engineer. The latter can assist those concerned with human variables by defining the practical problems that exist in industry, while the former can furnish data in regard to human capabilities and limitations. The areas relating to human factors that have been found to have implications for industrial safety are outlined. Emphasis is placed on the fact that safety will be improved if mechanical design is more intimately related to the anatomical, physiological, and psychological characteristics of the operators of machines. This implies that machines and working areas be designed from the man outward, with the instruments and controls considered as extensions of his nervous system and body appendages. On the engineering side, an advance analysis of all possible faults in the equipment and working areas is necessary, for if defects are present, it is only a matter of time until some operator fails and has an accident. These operational analyses may be made with the aid of such techniques as interviews and questionnaires, time and motion studies, and the study of errors and near accidents.

After the biologist has become familiar with the specific industrial problems and working situations he can furnish the anthropometric data necessary to insure minimum clearances, adequate accessibility to controls and materials, and proper seat design. Anthropometric data and methods of application are presented, which should assist in this regard.

Consideration is next given to the design of displays and controls. Displays impart to the various sense organs information regarding the functioning of the machine or the equipment. Factors affecting visibility are discussed in relation to size of critical detail, contrast, illumination, time of exposure, and color. Experimental findings are reported in regard to optimum shape, size, and design of dials and indicators. Many of these findings are applicable to the design of gauges, graphs, recording apparatus, and so forth, and various other industrial mechanical devices that are frequently misread or misinterpreted. The use of auditory, tactual, and kinesthetic displays that impart information to the workers is also discussed.

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[100] D. E. Goldman, A Review of subjective responses to vibratory motion of the human body in the frequency range 1 to 70 cycles per second, *Project NM-004-001, Report 1,* National Naval Medical Research Institute, March, 1948. See also *Ride and Vibration Data,* Special Publications Dept. (SP-6) Soc. Automotive Engrs., New York, 1950.

In the design of controls, special consideration is given to range, strength, speed, and accuracy of body movements in relation to the design of controls including location, shape, size, direction of movement, and gear ratio. The advantages of standardization of equipment are noted. Probably no better illustration could be given of the way in which the designer, the safety engineer, and the biological scientist should cooperate in the interest of safety than in the field of display and control problems. The physical variables of the environment are then considered briefly insofar as they relate specifically to the design of the working area.

Attributing accidents to human factors has sometimes been overemphasized; often the underlying cause of the accident can be traced to poor or inadequate design of equipment. Under such conditions, the wider use of biological and psychological data in the design of machines and working areas can contribute substantially to accident prevention. To achieve this, however, effective collaboration is necessary between the engineering and biological personnel.

CHAPTER V

Industrial Sanitation

M. A. SHAPIRO

Industrial sanitation is essentially a specialized application of community environmental health services. Within the purview of industrial sanitation are the principles involved in controlling the spread of infection or other insults to the health of the employee that are not inherent in the manufacturing process per se. For example, the industrial establishment that provides feeding facilities invites the disaster of food-borne infections and food poisoning if it fails to supply its employees with the utmost in sanitary food-handling facilities and practices. Even though the industry may contract for these services with an industrial catering concern, it does not absolve itself of this responsibility.

The areas that may be considered the province of industrial sanitation are: (*1*) provision of a safe, potable, and adequate water supply; (*2*) collection and disposal of liquid and solid wastes; (*3*) assurance of a safe food supply; (*4*) control and elimination of insects and rodents, especially those known to be vectors of disease; (*5*) provision of adequate sanitary facilities and other personal services; (*6*) maintenance of general cleanliness of the industrial establishment.

I. Provision of a Safe, Potable, and Adequate Water Supply

A. SOURCE AND REGULATORY CONTROL OF THE WATER SUPPLY

In the case of very large industries, the facilities for providing a safe and adequate water supply rival in size and complexity those of many a community. When water is supplied by the community, it is regulated as to safety and quality by the municipal or state authorities and, in the case of interstate commerce, by the Federal government. When no public supply is available at an economic cost, the industrial establishment must of necessity develop an adequate source of its own and usually it must treat the water at its own facilities to make it potable and safe. The control measures applicable to public supplies must be observed in the industrial supply. In most cases these are state regulations patterned after the United States Public Health Service *Manual of Recommended Water Sanitation Practice*[1] and the *Public Health Service Drinking Water Standards, 1946.*[2] These two documents, which are corollary, supply the needed information and recommended requirements as to the sanitation practices and standards suitable for evaluation of water and water supply systems required to maintain a physically, chemically, and bacteriologically safe water supply system. The methods of analysis that are acceptable are those set forth in the current edition of *Standard Methods for the Examination of Water and Sewage.*[3]

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[1] *Manual of Recommended Water Sanitation Practice, U. S. Pub. Health Bull.* No. **296,** 1946.

[2] *U. S. Public Health Service Drinking Water Standard, 1946, Reprint* No. **2697.**

B. DRINKING AND CULINARY WATER

Water supplied in drinking fountains and food preparation centers of the plant must be safe, clean, potable, and cool. Safety of the water may be threatened by contamination with disease-producing organisms, chemical toxins, and, with their increasingly wide use, radioisotopes. Maximum permissible concentrations of radioisotopes in drinking water are set forth in the National Bureau of Standards *Handbook 52.*[4] It should be borne in mind that the values given in this handbook for any isotope assume contamination by that isotope only. If the water is contaminated with several isotopes, then the maximum concentration of each isotope is proportionally reduced.

Drinking water should be maintained within the temperature range of 40 to 80° F. (optimal range is 45 to 50° F.). When cooling of the water is needed, it can be accomplished by mechanical refrigeration or by ice. When ice is used, it must not come in contact with the water since it can become a source of contamination.[5]

Most industrial plants have requirements for water of varying quality. In the majority of circumstances there is no need for these supplies to meet the high quality and bacteriological standards set for drinking and culinary water. The separate distribution and plumbing systems that convey this nonpotable water (any water supply not supervised as a drinking water supply must a priori be considered nonpotable) are potential health hazards and must not be used as a source of water for drinking purposes. The outlets provided on the nonpotable distribution systems should be posted plainly with permanently attached, durable signs indicating that the water is unfit for drinking, culinary, or ablutionary purposes.

A sanitary drinking fountain of approved design is the most efficient method of providing drinking water for employees. The American Standard Minimum Requirements for Sanitation in Places of Employment[6] states that: "Sanitary drinking fountains shall be of a type and construction approved by the health

[3] *Standard Methods for the Examination of Water and Sewage.* 10th ed., American Public Health Association, New York, 1955.

[4] *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water. Natl. Bur. Standards Handbook 52.*

[5] J. M. Dallavalle and R. R. Jones. Basic principles of industrial sanitation. *Am. J. Pub. Health,* **30,** 369 (1940).

[6] American Standard Minimum Requirements for Sanitation in Places of Employment, Z4.1-1955. American Standards Association, New York, 1955.

authorities having jurisdiction" (or meet local plumbing code requirements). "New installations shall be constructed in accordance with the requirements of the health authorities having jurisdiction, or, if there are no such requirements, in accordance with American Standard Specifications for Drinking Fountains, Z4.2-1942, or the latest revision thereof approved by the American Standards Association, Incorporated." In order to keep refrigeration needs to a minimum, individual disposable drinking cups may be provided. Whenever it is not feasible to provide a drinking fountain connected to the supply, an approved drinking water container with an approved fountain or individual disposable cups should be provided. In general, location of fountains may be determined by an over-all standard of one drinking fountain for each 50 employees. However, the distance the employee must travel to the nearest source may be a controlling factor in locating drinking water sources. (The Z4.1-1955 American Standard[6] requires that this distance be no more than 200 feet.) Similarly, wherever the employees are subjected to above-normal heat stress, this fact should be the controlling criterion for the location of a drinking water source.

In a few industries salt has been added to the drinking water supply to prevent heat exhaustion during the summer months. In one plant salt was added to the drinking water in one area starting in 1941 and was extended to the remainder of the drinking water in 1944. There has been a marked decrease in "heat sickness" since this program has been adopted. Acceptance by employees has been good. There were numerous complaints when the program was inaugurated and normally there are some calls in the late spring, when salinization is started. However, the concentration of salt does not exceed 0.1 per cent (1,000 p.p.m.), and when the units are started up in the spring, the concentration is gradually increased, taking about two to three weeks to reach the maximum concentration. This practice, together with more general use of water coolers, has reduced complaints to a very low point. The equipment at the salinizing stations consists of a brine tank, a metering device, and a proportioner. Grade A rock salt is purchased in 100-pound paper bags. It is charged into the brine tank daily, and a saturated solution is maintained in the tank. The solution is drawn from the tank and injected into the drinking water feed line by means of the proportioner and a fixed percentage of salt is maintained in the water line throughout its length.[7]

C. WATER USES IN INDUSTRY

The phenomenal growth and diversification of industrial production during the past half century have brought a need for large quantities of water of varying quality. Illustrative of this complex water demand is one chemical plant that had to develop five separate water systems to meet its manufacturing and employee needs. In general, water used in industry may be classified under eight headings:[8]

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[7] W. T. McCormick, personal communication.

[8] K. MacKichan. Estimated use of water in the United States, *U. S. Geol. Survey Circ.* No. **1115**, May, 1951.

(*1*) cooling, (*2*) solvent, (*3*) catalyst, (*4*) conveying medium, (*5*) plant cleansing agent, (*6*) production and distribution of heat and power, (*7*) employee use, and (*8*) fire fighting.

D. CONSERVATION OF WATER IN INDUSTRY

Another factor controlling the use of water in industry has been the necessity to conserve water resources, primarily but not exclusively in arid and semi-arid regions. Table 1 indicates the quantities of water required by certain industrial processes in the manufacture of their products. The table does not differentiate between consumptive use and processing water. The wide ranges reflect not only basic differences in processes or products, but also variations in water utilization practices. In arid regions, where the most rigorous conservation becomes essential, total intake of water is only a fraction of what it is where water is abundant and cheap, although water actually utilized in the process may be the same.

TABLE 1

Industry	Unit	Range of water use at different plants (gallons) Maximum recycling	No re-use
Butadiene	Ton	20,000	660,000
Sulfite pulp	Ton dry	70,000	133,000
Refined petroleum products	100 bbl.	15,000	1,500,000
Steel (rolled)	Ton net	15,000	110,000

It has been estimated that in 1950 the total industrial water use in the United States amounted to 80 billion gallons per day and this figure is expected to increase to 215 billion gallons per day by 1975—an increase of 170 per cent.[9] In general, the techniques utilized in water conservation practice may be classified as follows: (*1*) using less water by avoiding waste; (*2*) recycling—using water over again in the same process; (*3*) multiple or successive use—using water from one process for one or more additional processes in the same establishment; (*4*) substitution of source—using water from another establishment, or using nonpotable waters; (*5*) nonevaporative cooling techniques—using special methods to reduce the amount of water required for cooling.

Use of reclaimed water from sewage and industrial wastes has been practiced for many years in many parts of the world. In industry, its use has not been as widespread or as extensive as in agriculture. However, reclaimed waters have in the past been most suited for cooling purposes, since in this instance the quantity and temperature of the water are of greater importance than its quality. Powell[10] has described various purposes for which industry can employ reclaimed water, such as for plant processing water, boiler feed waters, certain sanitary uses, fire protection, air conditioning, and other miscellaneous uses.

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[9] Task Group A 4.D1 Report, Water conservation in industry, *J. Am. Water Works Assoc.*, **45**, 1249–1260 (1953).

[10] S. T. Powell, Some aspects of the requirements for the quality of water for industrial uses, *Sewage Works J.*, **21**, 36–50 (1948).

In addition to the general public health hazards involved in the utilization of a reclaimed effluent from a sewage treatment plant, there are quality considerations that arise from the concentration effects of the treatment process. The concentration of total salts may be increased measurably and the hardness of the water thus reclaimed can make its utilization impractical.

One obvious limitation that must be placed on the re-use of sewage and industrial wastes in industry is in those plants manufacturing products for human food, since the degree of treatment and the control required to keep the reclaimed water from coming in contact with the food would be so high as to make such use too costly. In addition, reclaimed effluents cannot be utilized in industries where such water would come in contact with human beings.

Arnold, Hedger, and Rawn in their report on the reclamation of water from sewage and industrial wastes in Los Angeles County, California, in April, 1949, drew the following conclusions.[11] *(1)* There are a number of important factors limiting the direct use of water reclaimed from sewage in industry. In addition to public health hazards and total salt concentration, considerations of the hardness of the water may be of material importance. *(2)* In general, the direct re-use in industry of acceptable water reclaimed from sewage is tolerated and encouraged in manufacturing processes that do not involve contact between the reclaimed water and human beings or foods to be consumed by humans. *(3)* The most obvious direct re-use for reclaimed sewage water is for cooling and condensing operations.

E. CROSS CONNECTIONS

The variety of water supplies within a plant and the re-use and recycling of industrial water are of interest to the sanitary engineer, beyond their conservation implications, to the extent that they present actual or potential hazards to the cleanliness, safety, potability, and coolness of the drinking and culinary water supplies. Such danger occurs when there are any connections between a water supply of known potability (primary source) and a supply of unknown quality (the used water), and when there are plumbing defects that may allow sewage and toxic materials to enter the drinking water distribution system. The possibilities of contaminating a potable supply by a nonpotable supply when unauthorized or unsafe connections are made are legion. Pressure variations in distribution systems are not uncommon, and when reduced pressure conditions occur in a potable system connected with another of unknown potability having a higher pressure, the flow will be from the unknown-potability system into the potable system. Such and other potentially dangerous situations in water systems are termed cross connections.

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[11] C. E. Arnold, H. E. Hedger, and A. M. Rawn, "Report upon the Reclamation of Water from Sewage and Industrial Wastes in Los Angeles County, California." Report prepared for County of Los Angeles, California, 1949.

Spafford[12] reports that the 40 water-borne epidemics recorded from 1907 to 1953 in Illinois have resulted in 13,000 known cases of illness and 200 deaths. Eighteen of the outbreaks, almost half of the total, were caused by some type of faulty piping or plumbing arrangement that permitted sewage or other contaminated water to enter a safe water system, either at the source or in the distribution facilities. This experience is in agreement with the general observation that cross connections between safe and raw or unsafe water systems have been the greatest single cause of water-borne epidemics.

Contamination of the potable water supply by means of cross connections or defective plumbing fixtures may take place *(1)* by the occurrence of a vacuum in the supply lines causing back-siphonage of contaminated material; *(2)* by the development of pressure in the fixture, appliance, or piping system to which the water supply is connected that is greater than that in the supply system itself; and *(3)* through the activities or actions of vermin, birds, or small animals in parts of the supply system not under pressure, or by dust reaching water-holding devices.[13]

Periods when reduced pressure or partial vacuum situations may occur within a potable water system result from the following circumstances or by a combination of a number of them:

1. The interruption of the supply for maintenance of the municipal or service supply main.
2. Excessive demand placed upon the supply mains during fire or other emergencies.
3. Complete failure of the supply due to breaks in the mains, interruption of pumping, either by mechanical failure or power shut-off, or deficient water supply.
4. Freezing of mains or service lines in extremely cold weather.
5. Excessive friction losses due to inadequate size of mains or service lines, or due to reduction of the effective diameter of pipes caused by deposits and encrustations.
6. Occurrence of negative water hammer pressure waves.
7. Operation of long pump suction lines.
8. Condensation of steam within boilers, hot water systems or such units as hospital sterilizers.

F. ELIMINATION OF CROSS CONNECTIONS

The safest method of making two supplies available to a building is by the use of an unobstructed vertical fall through the free atmosphere between the lowest opening from any pipe supplying water to a reservoir and the highest possible level the water may reach in the reservoir. The minimum air gap thus provided should be two times the diameter of the effective opening and in no case less than four inches. In addition a float valve arrangement should be installed to cut off the supply when the water reaches the free overflow level. The overflow channel or pipe should allow free discharge to the atmosphere with no enclosed connection to the sewer (Figure 1). A suitable swing ell may be utilized where the potable supply and the secondary supply are not required to be available at all times (Figure 2).

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[12] H. A. Spafford, Cross connection hazards and protection. *J. Am. Water Works Assoc.* **46**, 993–998 (1954).

[13] A. B. Cronkright and A. P. Miller, Plumbing and public health. *U. S. Pub. Health Bull.* No. **256**, 1940.

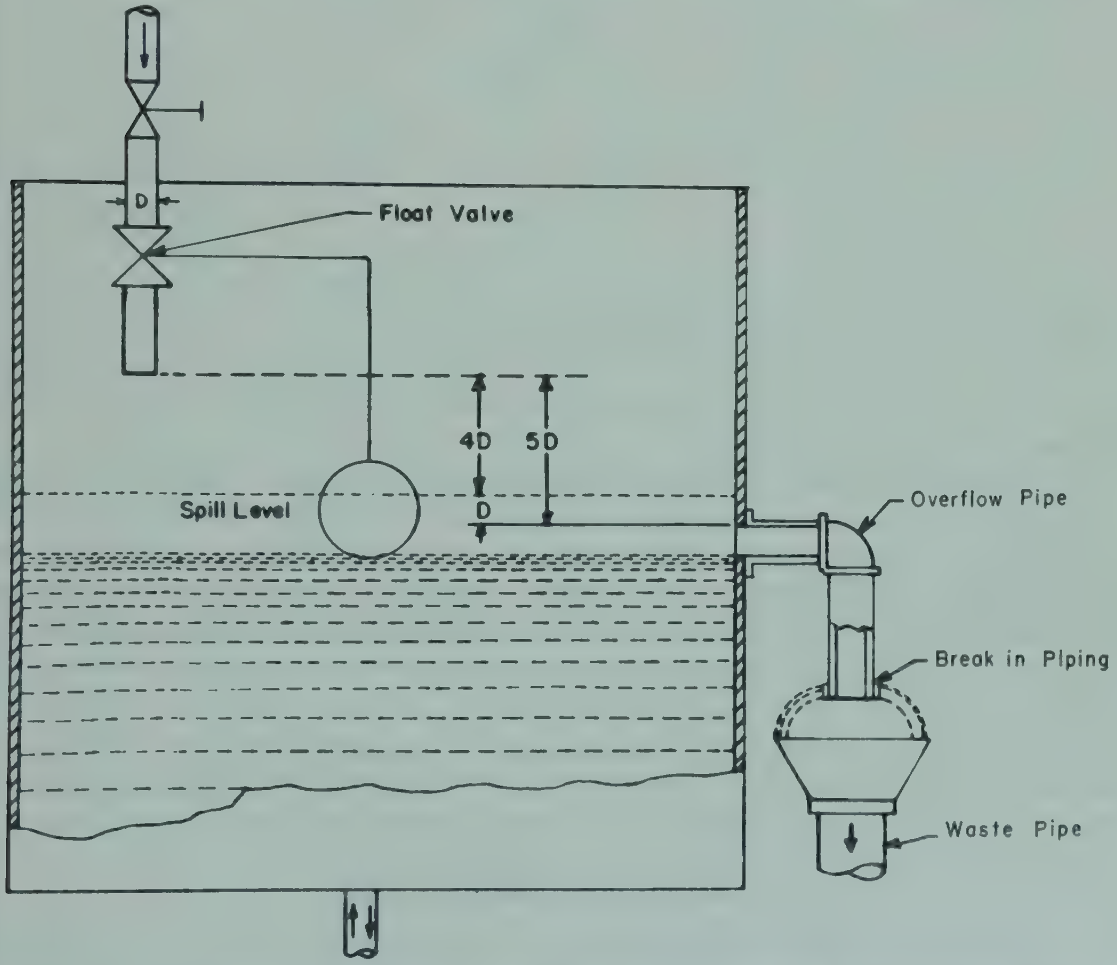

Figure 1. A method of connecting a public water supply to a private water supply through a tank or reservoir.

To prevent backflow from fixtures in which the outlet end may at times be submerged, such as a hose and spray, direct flushing valves and other devices in which the surface of the water is exposed to atmospheric pressure, a vacuum breaker should be installed. There are two general types of vacuum breakers: (*a*) moving part and (*b*) nonmoving part. Whichever type is used it should meet

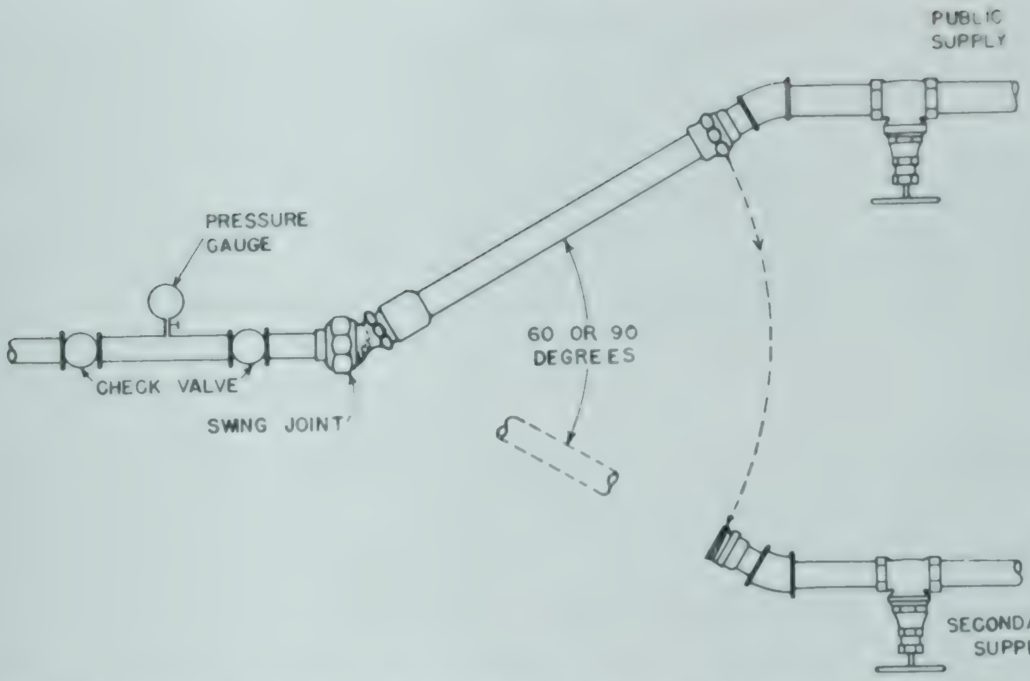

Figure 2. A method of connecting public water supply or secondary supply to a single distribution system.

test requirements of the American Standard for Backflow Preventers in Plumbing Systems, A40.6-1943.[14]

All fixtures supplied by a faucet should have an air gap, which is measured vertically from the end of the faucet spout or supply pipe to the flood level rim of the fixture or vessel. The minimum air gap provided should be twice the diameter of the effective opening but no less than one inch. When affected by a near wall, the minimum air gap should be 1½ inches. Other conditions should meet the requirements of the American Standard for Air Gaps in Plumbing Systems, A40.4-1942.[14]

Connections to condensers, cooling jackets, expansion tanks, overflow pans and other devices that waste clear water only should be discharged through a waste pipe not directly connected to the drainage system, but having an air gap.

G. CROSS CONNECTION SURVEYS

In an existing building or structure it is advisable to conduct a comprehensive survey of the entire plumbing system in order to determine the cross connection hazards. After such a survey has been made, it is then feasible to establish a prevention program based upon systematic control of all new piping installations and fixture changes. The cross connection survey should include an examination of all piping systems, plumbing fixtures and their specifications, potable water supply connections to industrial equipment, pressure on the potable water distribution system, all backflow prevention devices, adherence to a safety color code, and so forth. The information thus obtained can then be profitably utilized whenever changes in the plumbing system have to be made.

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[14] American Standards Association, New York.

II. Collection and Disposal of Liquid and Solid Wastes

Wastes are end products of any manufacturing process no matter how efficient or well designed its operation. These industrial wastes, as well as the wastes produced by the plant personnel, must be rendered innocuous and disposed of, for they may carry chemical toxins and disease-producing organisms that are hazards to the health of the plant personnel, the population of the surrounding community (primarily through pollution of drinking water), and the plant and animal life of the area.[15] The recent accidental discharge of a tank of plating solution containing $1^1/_2$ tons of sodium cyanide industrial wastes into a city sewer system and to the river that was the source of water supply for a large community illustrates the hazard of uncontrolled waste disposal.[16] Outbreaks of typhoid fever and other enteric diseases traceable to contamination of a water supply with untreated sewage from human carriers are well known to sanitary engineers. Of equal importance is the continual and more subtle chemical, physical, and biological degradation of the water resources of the country by indiscriminate release of untreated industrial waste.

In recent years, a whole new field of industrial waste collection and disposal has developed, with specialists devoting their full attention to the complex problem of the proper disposal and salvage of wastes. These men have co-operated with industrial and chemical engineers in the design of processes and equipment that reduce waste production to a minimum. This approach to the waste disposal problem in industry parallels the objectives of the industrial hygienist, who desires that hygienic factors receive the same basic consideration in the course of analysis and design as do the requirements for satisfactory performance of the equipment.

In addition to the wastes of the more conventional industrial processes, the problem of proper disposal of wastes from the atomic energy industry is of rapidly growing magnitude and concern. Although the uniqueness of its hazards, operations, products, and wastes places the industry in a special category and the attack on the problem requires specialized knowledge, it should come within the scope of the industrial wastes engineer.[17]

A recent example of planning that anticipated problems of waste collection and disposal occurred in the design of a steel plant.[18] Here, the problem was one of using very large quantities of water in the manufacturing process while at the same time maintaining the quality of the water in the river into which the plant's waste waters were to be discharged. Wastes originating from the plant included acids, alkalies, soluble oils, insoluble (floating) oils, mill scale, flue dust, and sanitary sewage. Consideration of the potential waste problems and agreement on objectives before the basic steel-producing facilities were constructed permitted engineers a large degree of freedom in the choice of treatment sites, processes, and installations. This same early planning allowed unification of design of all water, drainage, sewerage, and waste treatment facilities; the working out of processes wherein some of the discharges were used as means for treating some of the others; and, in some instances, recovery of industrially valuable products.

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[15] L. B. Dworsky, Industry's concern in pollution abatement and water conservation measures, *U. S. Pub. Health Repts.*, **69**, 37 (1954).

[16] B. A. Poole, R. H. Holtje, and W. G. Belter, Control of accidental discharge of cyanide solutions, *Sewage and Ind. Wastes*, **26**, 1382 (1954).

[17] J. A. Lieberman and A. E. Gorman, Treatment and disposal of atomic energy industry wastes, *Proc. Am. Soc. Civil Engrs.*, **80** (Separate No. 422), (March, 1954).

A. SEWAGE AND OTHER LIQUID WASTES

The sanitary sewage portion of the liquid wastes of an industry, if kept separate from the industrial wastes, offers no special problem to the sanitary engineer. The economics of any particular situation dictates whether the ultimate disposal facility will be the community's or a private sewage treatment plant. Should the industry be located within reasonable distance of a municipal sewerage system, connection to it for ultimate disposal through the community's sewage treatment plant is preferable to construction and operation of disposal facilities by industry. In recent years many industrial communities have established sewer rental charges and rate schedules to meet the increased cost of sewer maintenance and treatment of the liquid wastes of industry in the municipal sewage treatment facilities. Cincinnati, Ohio,[19] recently enacted an "Industrial Wastes Ordinance," which defines "normal sewage" as having not more than 300 p.p.m. suspended solids nor 240 p.p.m. BOD (Biochemical Oxygen Demand) nor 50 p.p.m. of other soluble matter (grease or oil). A surcharge is being levied against industry for the treatment of permissible wastes that place an unreasonable load on pumping, treatment, or disposal. The method of liquid waste disposal to be utilized in any particular situation varies with the strength and character of the waste as measured by its chemical, physical, and biological constituents and with the dilution capacities and uses of the receiving body of water.

In general, treatment plants are described as either *(1)* "primary," consisting of removal of settleable and floatable matter, or *(2)* "secondary," or "complete," which, in addition to the foregoing, remove or change the nature of the colloidal and dissolved matter in the waste.

Treatment of liquid wastes consists of at least one, but more often two or more, of the following processes, in a variety of combinations:

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[18] R. Nebolsine, Waste disposal at a steel plant: 1. General problems, *Proc. Am. Soc. Civil Engrs.*, **80** (Separate No. 492), (September, 1954).

[19] *Eng. News-Record*, **154**, No. 26, 40–43 (June 25, 1953).

Dilution—depending upon the present and future capacity of the receiving body of water to absorb the physical, chemical, and biological waste load.
Sedimentation—removal of settleable solids by hydraulic separation.
Screening and centrifugation—removal of solids by mechanical separation.
Flotation—use of flotation agents, air, and subsequent skimming.
Chemical precipitation—coagulation and flocculation of particles for subsequent hydraulic separation.
Biological treatment—(*a*) intermittent or continuous treatment in sand or gravel beds, (*b*) introduction of air or oxygen in presence of activated solids, (*c*) anaerobic decomposition of solids in digestion tanks.
Lagooning—supplementary sedimentation, equalization of composition and possible oxidation by photosynthesis where the wastes are not toxic.
Application to land—use of spray or surface irrigation.
Disinfection and odor control by chlorination.

B. SOLID WASTES

The maintenance of a sanitary environment in the industrial establishment demands the prompt and proper collection, storage, and ultimate disposal of solid wastes. Most manufacturing processes produce varying quantities of solid wastes. In many cases a portion of these wastes is either salvageable or recoverable. However, such wastes as floor sweepings and garbage from industrial food-handling establishments must be disposed of as rapidly as possible. The relationship between improper and insanitary solid waste–handling methods and employee health is not as direct as, for example, when the potable water supply of an industry becomes contaminated. However, improper storage of organic solid waste is an open invitation to rodent infestation; and in those areas where murine typhus or plague are endemic, the possibility of the transmission of these diseases is ever present. The breeding of flies and other insects is in direct proportion to the manner in which putrescible organic wastes are handled. For temporary storage a wide variety of receptacles for solid waste materials is available. These receptacles must be placed in strategic locations within the industrial establishment in order to promote the orderly collection of solid wastes and the prevention of scattering of material. In recent years a number of portable large-capacity waste receptacles, which can be transported on a special truck, have become available. This type of receptacle allows placement in strategic areas where the wastes accumulate and further provides for easy dumping and ease of cleaning. Furthermore, they can be manufactured in a number of shapes and sizes in order to meet a wide variety of industrial situations.

In general, three acceptable methods of solid waste disposal are available at this time: (*1*) incineration, (*2*) sanitary landfill, and (*3*) composting. A fourth method, grinding and disposal in a water carriage system, is available for organic wastes. Many types of incinerators are available to the industrial establishment for disposal of solid wastes. The design of incinerators has progressed rather rapidly in the past few years. It is sufficient to indicate that incinerators have been designed for the disposal of chemical wastes, and for large quantities of solvents; to incinerate varnish wastes and dispose of the varnish fumes innocuously; especially for the disposal of water-aniline mixtures; and with a multiple hearth for the incineration of vacuum-filtered primary treatment sewage sludge. In recent years air-pollution control officials have leveled a valid charge against many industrial incinerators, primarily because of improper operation or overloading beyond design capacity, which results in troublesome air-pollution problems—production of obnoxious odors and large amounts of fly ash.

The sanitary landfill method of solid waste disposal evolved out of a need to control the open dump. Essentially, this method utilizes heavy equipment, such as crawler tractors, to spread and compact the refuse in cells of approximately one third of its original volume, and then cover the compacted waste with an earth cover two feet in depth. The waste is placed in the cells, which are either excavated or placed in low-lying areas, and then covered. In order to be maintained in a sanitary condition, the landfill must be originally designed as an engineering project and properly operated at all times. Without such control the sanitary landfill reverts to the open dump status.[20]

III. Assurance of a Safe Food Supply

The objective of food sanitation, as of other environmental health activities, is the prevention of illness. It is evident that the technological and economic aspects of purveying food play an important role in the application of effective control measures. In addition, it should be the aim of a food sanitation program to accomplish its goal without reducing the nutritional value of the food.

A. ILLNESSES DUE TO INGESTION OF FOOD

Illnesses due to the ingestion of food vary in their nature. They may be divided broadly into four classes: (*1*) infections, which are due to the ingestion of living pathogenic organisms (bacterial or viral) contained in the food; (*2*) intoxication resulting from the ingestion of food in which preformed microbial toxins have developed; (*3*) animal parasitism; and (*4*) poisoning by certain chemically contaminated food.

1. Microbial Infections

In the United States many important food-borne diseases are caused by bacterial contamination. Some of the microbial infections spread by contaminated food are: salmonella infections (including typhoid fever), diphtheria, bacillary dysentery, scarlet fever and other streptococcal infections, staphylococcal infections, tularemia, Weil's disease, and tuberculosis. It is probable that viral diseases are also transmitted in food, but to date the difficulty of propagating and identifying these organisms has made this an unproved assumption in most cases. When contamination is heavy or when the particular bacteria are highly virulent, infection may follow ingestion of the food even though it has been stored under optimal conditions. More frequently, however, the bacteria originally contaminating the food multiply to dangerous numbers during prolonged storage at a temperature between 50 and 150° F. (the so-called incubation zone). Foods most commonly found to be vehicles of the bacterial infectious agents are milk and cream, ice cream, seafoods, meats, eggs, salads, mayonnaise and salad dressings, custards, cream-filled pies, eclairs, and other filled pastries. Unfortunately, the food contaminated by these disease agents is not necessarily decomposed or altered in taste, odor, or appearance.

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[20] Analysis of refuse collection and sanitary landfill disposal, *Tech. Bull.* No. 8, Series 37, University of California, Berkeley, 1952.

There are different ways in which bacterial contamination of food may occur. Infected persons may transmit bacteria by droplets (sneeze or cough) from the respiratory tract, by discharges from skin infections of the hand, and by contamination of hands with feces, nasopharyngeal secretions (failure to wash after blowing the nose), and discharges from open or draining sores elsewhere on the body (failure to keep these covered). In some instances the infected person is without symptoms or signs of illness and therefore difficult to detect and control. Another source of bacterial contamination of food is the multiplication of bacteria in improperly cleaned utensils with transfer to foods subsequently served, stored, or prepared in them.

Mice, rats, and roaches may contaminate foods and utensils by bacteria carried mechanically on their feet and bodies from an infected to a noninfected area, or they may contaminate food with their urine and feces which may contain pathogenic organisms such as, in the case of rats, *Salmonella* and *Leptospira icterohemorrhagica* (cause of Weil's disease). The source of infection in meat and poultry may be their infection before killing, or contamination may occur subsequent to killing, as with other foods.

The clinical symptoms of acute gastric enteritis due to bacterial infection usually have their onset 6 to 24 hours after ingestion of the infected food. Cramping abdominal pain, diarrhea, nausea, and vomiting are the chief manifestations; often these are accompanied by headache, pyrexis, and general malaise.[21]

2. Bacterial Food Poisoning

Bacterial food poisoning is caused by bacteria that, while usually harmless to man, produce toxic substances when they grow in food. These toxins, when ingested in sufficient amount, give rise to serious or fatal disease, even though there is no further multiplication of the organisms in the body. Bacteria of the staphylococcus group, often found in skin infections (pimples, boils, carbuncles) and respiratory tract infections, may form a virulent enterotoxin when allowed to grow in food. The symptoms of staphylococcal intoxication consist of nausea, vomiting, cramping abdominal pain, and diarrhea. In severe cases, blood and mucus may be found in the stool and vomitus. The chief distinguishing characteristic between food poisoning from toxins and enteric disease from pathogenic bacteria carried in food is the time of onset of symptoms. In staphylococcal intoxication, this is often less than 3 hours after the ingestion of the contaminated food and rarely longer than 6 hours. On the other hand, in bacterial infections a delay of 6 to 24 hours between ingestion of food and onset of symptoms is more likely. The rapidity of onset and uniform distribution of food poisoning symptoms in a group of people make it possible to determine the meal and particular foods in the meal responsible for poisoning.

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[21] K. F. Maxcy, "Contagious Disease Spread Largely through Fecal Discharge." *Preventive Medicine and Hygiene*. 8th ed., Appleton-Century-Crofts, New York, 1956, Ch. 3.

3. Animal Parasitism

Some of the diseases caused by ingestion of food contaminated with animal parasites are amoebiasis, trichinosis, and tape worm infestation. In the instance of infection with *Endamoeba histolytica* (causative organism of amoebic dysentery), the source and transmission of infection is similar to that of other enteric pathogens, such as *Shigella* and *Salmonella*. The problem is somewhat different for *Trichinella spiralis* and the tapeworms, for in these cases the infectious organisms are present in an animal, for example, swine, beef, fish, before the time of killing. Prevention of disease caused by, and control of, these parasites depend on inspection and selection of food at the time of purchase as well as on proper preparation, since the heat of prolonged cooking will destroy the organisms.

4. Toxic Chemicals

Accidental contamination of foods by toxic chemicals is an additional hazard. Acute poisonings are characterized by sudden onset from a few minutes to two hours after ingestion of the chemical. The more common poisons reported as foodborne are cadmium (from metal-plated utensils), sodium fluoride (from roach powder), and arsenic (from insecticides). Others frequently mentioned are antimony, zinc, lead, and copper.

The recent appearance of compounds such as the aliphatic and aromatic amines as boiler feedwater conditioners may present an additional hazard in the preparation of foods. Wherever steam may come in direct contact with food, the toxicity, type, and quantity of boiler feedwater conditioners should be ascertained. Complete physical separation of the food and steam from the boiler is recommended.

The revised American Standard Minimum Requirements for Sanitation in Places of Employment[6] states (10.1.1) that: "In all places of employment where employees are permitted to lunch on the premises, an adequate space suitable for that purpose shall be provided for the maximum number of employees who may use such space at one time. Such space shall be separate from any location where there is exposure to toxic materials." It further states (10.1.3) that: "No employee shall be permitted to store or eat any part of his lunch or eat other food at any time where there is present any toxic material or other substance that may be injurious to health." Item 10.1.4 states that:

> In every establishment where there is exposure to injurious dusts or other toxic materials, a separate lunch room shall be maintained unless it is convenient for the employees to lunch away from the premises. The following number of square feet per person, based on the maximum number of persons using the room at one time, shall be required:

Persons	Sq. ft.
25 and less	8
26–74	7
75–149	6
150–499	5
500 and more	4

B. FOOD HANDLING

The food handler educated in the proper methods of handling foods, glassware, and utensils and in good personal hygiene is a cornerstone of a safe food supply. In food sanitation the health of the food handler is of primary importance, and every effort should be made to exclude from the food establishment any sick or injured employee with a discharging wound or lesion. This does not mean that a system of frequent medical and laboratory examinations of food handlers is recommended. On the contrary, these have been found repeatedly to be too costly when measured in terms of the results achieved. It is believed today that education of the food handler to report promptly any illness is a more effective means of reducing food-borne disease. In many localities health departments are prepared to provide pre-employment or in-service food handler training programs, and a variety of training manuals and visual aid materials are available.[22]

In the handling of foods, particularly those previously mentioned as being sources of infection or intoxication, care must be taken to keep them out of the incubation zone; that is, they must be refrigerated at a temperature below 50° F. or kept hot at 150° F. or above. The exception to this rule is that during preparation, serving, or transportation the food may be kept at intermediate temperatures for a period not exceeding two hours. Indicating thermometers of proven accuracy should be installed in all refrigerators. Common deficiencies found in refrigerated food storage are the overloading of the refrigerator, which prevents the free circulation of cold air, and the storage of foods in deep containers, which do not allow the total mass of the food to cool to 50° F. or less within the prescribed two hours. Further provisions for the continual vigilance against possible chemical contamination must be exercised by prohibiting the use of cadmium-plated utensils, the use of galvanized utensils for cooking, and the use in food preparation and serving areas of roach powders with sodium fluoride, cyanide metal polish, and so forth.

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[22] *Sanitary Food Service (Instructors Guide), U. S. Pub. Health Service Publ.* No. **90.**

In view of the widespread custom, especially in the United States, of providing cubed and crushed ice in drinking water and beverages, it is of interest to note two reports on the sanitary quality of such ice.[23] Both studies report that such ice often fails to meet sanitary standards and is contaminated with *Escherichia coli*, clostridia, micrococci, and streptococci. A suggested control method is to provide a chlorine disinfecting solution (approximately 2 p.p.m.) in which the ice is placed.

C. KITCHEN AND KITCHEN EQUIPMENT DESIGN

The Ordinance and Code prepared by the United States Public Health Service[24] and adopted by the American Standards Association[6] as a minimum standard whenever local regulations do not apply to the industrial food-handling establishment provides for certain materials of construction, minimum lighting, and ventilation requirements. The design of kitchens is a problem in materials handling, batch preparation, and small quantity distribution. The designer must provide for the greatest ease in performing a large variety of tasks, usually in too crowded quarters.

It behooves the kitchen designer to provide sufficient space in this important working area that the tasks of preparing food and washing of dishes and utensils may be accomplished in a sanitary manner. Separation of activities—food preparation, baking, and washing—is preferable to combining them in one room. The location of kitchen equipment in relation to ease of cleaning is of great importance. Too often stoves, steam kettles, peelers, and mixers are placed close to walls allowing dirt to accumulate and providing excellent breeding and hiding places for roaches.

Tables and stands should have shelves no less than six inches off the floor. Fixed kitchen equipment should be sealed with impervious material to the wall or, alternatively, kept away from the wall with sufficient space between them to allow for easy cleaning. All work surfaces should be made of impervious, noncorrosive, and easily cleaned material. When wood is used it should remain unpainted and be scrubbed daily. Cutting, peeling, and other mechanical equipment should be designed to eliminate dirt-accumulating crevices and to be readily disassembled for cleaning. Recently a voluntary organization representing the public health profession, business, and industry has published a series of standards for Soda Fountains and Luncheonette Equipment, Food Service Equipment, and

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[23] E. W. Moore, E. W. Brown, and E. M. Hall, Sanitation of crushed ice for iced drinks, *J. Am. Pub. Health Assoc.*, **43**, 1265–1269 (1953). V. D. Foltz, Sanitary quality of crushed and cubed ice as dispensed to the consumer, *U. S. Pub. Health Repts.*, **68**, 949–954 (1953).

[24] *Ordinance and Code—Regulating Eating and Drinking Establishments* (Recommended). U. S. Public Health Service, Washington, 1943.

Spray Type Dishwashing Machines; others are in the process of preparation.[25] These standards are of value in identifying equipment that has been tested to meet exacting sanitation requirements.

D. FOOD VENDING MACHINES

The use of automatic vending machines in the purveying of food has developed rapidly in the past decade. Vending machines are available that serve hot beverages, cold carbonated and noncarbonated beverages, sandwiches, and pastries. A recommended ordinance and code has been published by the Department of Health, Education, and Welfare.[26] The following considerations may be used as a guide for the selection of automatic food vending machines.

All surfaces that come in contact with the food should be constructed of smooth, noncorrosive, nontoxic materials. All flexible piping should be nonabsorbant, nontoxic, easily cleanable, and remain unharmed when treated with the more common disinfecting agents.

Vending machines purveying perishable foods should be refrigerated. Their design should include an automatic temperature-controlled shut-off that will prevent the machine from operating whenever the temperature in the storage compartment rises above 50° F.

In general, the design of the machine should allow easy accessibility for cleaning and disinfecting all surfaces that come in direct contact with the beverage or food.

Whenever disposable cups are furnished they should be stored in protective devices, and it should be possible to reload them without touching the lips or interior surface of the cups.

The drip receptacles in beverage vending machines should be provided with a float switch that would prevent the machine from operating when the liquid in the receptacle reaches a certain level. The vending area of the machine should be protected from dust, dirt, vermin, and possible mishandling by patrons by means of self-closing gates or pans.

The cleaning of tanks, containers, and other demountable equipment should be done at a central location. Whenever cleaning is accomplished at the vending machine, a portable three-compartment sink should be provided in order to wash, rinse, and disinfect all demountable equipment properly. At such points water and sewer facilities should be provided.

The food and drink for the vending machines should be stored and handled as they would have to be to meet the requirements of food-handling establishments. A good rule is to offer for sale only packaged foods that were prepared at a central commissary. All perishable food should be coded as to place of origin and date of preparation. Perishable food that remains unsold, even though it has been properly refrigerated, should be disposed of at frequent intervals.

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[25] Soda Fountain and Luncheonette Equipment, Standard No. 1; Food Service Equipment, Standard No. 2; Spray Type Dishwashing Machines, Standard No. 3. National Sanitation Foundation, Ann Arbor, Mich.

[26] The Vending of Foods and Beverages, A Sanitation Ordinance and Code, Recommendations of the Public Health Service, U. S. Department of Health, Education, and Welfare, 1957.

No vending machines should be located in areas where there is exposure to toxic materials.

IV. Control and Elimination of Insects and Rodents

A. INSECT CONTROL

Except for the food and other industries dealing with products that may serve as food for insects, the problem of controlling these pests is dependent largely upon good housekeeping. The more general problem of control of arthropods and arthropod-borne disease cannot be accomplished on a restricted scale as in a single industrial establishment, but must be a community-wide or regional undertaking of considerable magnitude. It should be understood, of course, that whenever an industry is located in an infested area it should cooperate with the agency effectuating control.

Although such insects as flies and roaches are of lesser health importance, their number and prevalence are a good general index of the "sanitation" practiced in the establishment. Of direct interest is the proof obtained of the relationship between fly prevalence and the infections, diseases, and deaths caused by the bacillary dysentery organism.[27] Field studies showed that bacillary dysentery was materially reduced in a community when effective fly control measures were undertaken.

The most direct method of dealing with an insect infestation problem is to eliminate breeding places. Wherever garbage, rubbish, or other organic matter is allowed to accumulate and become exposed to insects, it produces ideal conditions for their development. In the food-handling areas nourishment is available and harborage provided in cracks, crevices, voids, and other unused spaces.

The more common insect invaders are the roaches (German cockroach *Blatella germanica*, American cockroach *Periplaneta americana*, Australian cockroach *Periplaneta australasiae*, Oriental cockroach *Blatta orientalis*, brown banded cockroach *Supella supellectilium*) and flies, of which 90 to 95 per cent are houseflies *Musca domestica* and blowflies *Phaenicia*.[28]

The use of insecticides is recommended when infestation is heavy and after the environmental conditions favoring breeding have been eliminated. A wide variety of insecticides (which are also of danger to the user) is available. These may be classified as: (*1*) contact poisons, (*2*) residual insecticides, (*3*) stomach poisons, and (*4*) respiratory poisons (fumigants).[29]

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[27] D. E. Lindsay, W. H. Stewart, and J. Watt, Effect of fly control on diarrheal disease in an area of moderate morbidity, *U. S. Pub. Health Repts.*, **68**, 361 (1953).

[28] M. E. Parker, "Safe and Effective Insect Control," *Food-Plant Sanitation*, McGraw-Hill, New York, 1948, Ch. 9.

[29] A. E. Michelbacher and D. P. Furman, Control of household insects and related pests, *Calif. Agr. Extension Service Circ.* **172**, College of Agriculture, University of California, Berkeley, 1951.

B. RODENT CONTROL

Infestation of the industrial plant by rodents, apart from the health hazards they produce as vectors of disease (bubonic plague, endemic or murine typhoid fever, salmonellosis, and Weil's disease), can be a tremendous economic drain. As a general principle, in the community the destruction of food, crops, merchandise, and property by rats is of a large enough magnitude to justify suppressive measures even if rats were not responsible for human disease. Rats, by their destructiveness and pollution of food, have gained the unenvied fame of being the worst mammalian pest in civilization. Davis (1950)[30] estimated about one rat per 35 people in New York City and about one rat per 20 people in Baltimore. As pointed out by Davis, the regulatory factors in any problem of species management can be classed in three main groups: (*1*) environment—which includes availability of food and protective shelter; (*2*) predation—which includes animals that feed upon the species, trapping, poisoning, and disease; and (*3*) competition—the fight for a limited supply of environmental necessities.

Control of the rodent population should be based primarily on a change of the environmental conditions so that the rodents are deprived of food and shelter. When this is accomplished, the rodent population will be reduced by competition among themselves. Since the reproductive rate of Norway rats (they reproduce during all seasons of the year, with a maximum in both spring and fall occurring in many areas) is on the average of 20 rats per year, it is evident that should the environmental conditions be favorable, killing procedures will be of little effect in reducing the population and maintaining it at a low level.[31]

C. RATPROOFING (BUILDING OUT THE RAT)

Ratproofing is a term applied to procedures for controlling the portals of entry of rats into a structure. Rats, being extremely cautious, nocturnal mammals, prefer small openings through which to enter a building. Only when they are subjected to peril will they venture away from normal pathways. The points of ingress and egress of rats that must be guarded against, in particular, are any openings around pipes, unused stacks and flues, ventilators, and hatches.

All new buildings should be designed and constructed to be ratproof. Foundations must be continuous and extend not less than 18 inches below the ground level and should always be flush with the under surface of the floor above. Floor joists should be imbedded in the wall and the space between the joists filled in and completely closed to the floor level, and all construction materials should be as ratproof as possible.[32] In industry, the most frequent shelters for rats are areas surrounding the cafeteria, the lunch rooms, and other eating areas, although no place that affords sufficient food and shelter is immune to rat infestation. The office in which employees are permitted to eat their lunch is often rat infested, the scraps left in the waste baskets providing the rats with a good food source. All other organic wastes provide the rats with an additional good source of food.

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[30] D. E. Davis, Perspective on rat control, *U. S. Pub. Health Repts.*, **67**, 888 (Sept., 1952).

[31] D. E. Davis. "Control of Rats and Other Rodents," in K. F. Maxcy, *Preventive Medicine and Hygiene*. 8th ed., Appleton-Century-Crofts, New York, 1956, Ch. 8.

[32] *Rat-borne Disease; Prevention and Control.* Communicable Disease Center, U. S. Public Health Service, Atlanta, Ga., 1949.

D. KILLING RATS

Trapping by means of snap and cage traps is a method of killing rats that requires great skill and ingenuity, rats being rather wary mammals. Killing by use of rodenticides has advanced greatly in the past two decades. The most widely used and oldest poison is Red Squill, which has the advantage of having an emetic action that protects humans and all animals with the ability to vomit. Barium carbonate and phosphorus, utilized in the past, are not widely used now because of their unpredictable results. The newer rodenticides are Antu, a specific for Norway rats; sodium fluoroacetate (1080), an extremely powerful poison for all animals, which requires extreme caution in its use and which has therefore been prohibited in many localities because of human deaths; and Warfarin (a derivative of dicumarol), an anti-coagulant that causes internal hemorrhage in the rat, which, although affecting other animals, has a large factor of safety because of the low dosage (0.025 per cent) used in the baits.

In certain enclosed structures, primarily aboard ships, fumigants, such as hydrocyanic acid gas or carbon monoxide, are used for quick and nearly complete elimination of rats.

V. Provision of Adequate Sanitary Facilities and Other Personal Services

The personal hygiene practices of employees carry many health implications without reference to their employment. For instance, the disease-transmitting potential from failure to clean the hands after defecating, or the skin diseases resulting from poor body cleansing, may not be related to the person's job. There are, however, health problems relating to personal hygiene practices that occur in industry exclusively. Such problems are related to ingestion of chemical toxins or disease-producing organisms and to local skin, conjunctival, or mucous membrane inflammation due to sensitivity or direct irritative action of industrial chemicals.

Schwartz states that uncleanliness "is probably the most important predisposing cause of occupational dermatitis" (cf. page 447). Uncleanliness of the working environment exposes the worker to large doses of external irritants. Personal uncleanliness not only does the same, but also permits external irritants to remain in prolonged contact with the skin. Workers wearing or carrying to their homes their dirty work clothes may even cause dermatitis in other members of the family who come in contact with soiled clothes, or even among unsuspecting workers who clean them.

Where the employee is exposed to toxic materials, or if he is a food handler, the need for the optimum in clean, well-lighted, and well-ventilated washing and locker facilities becomes imperative from the point of view of both protecting the health of the individual employee and minimizing the possibility of his transmitting infections to others. Unless the toilet and washroom facilities are easily cleanable, adequate in size and number, and accessible, the personal hygiene habits of employees in industry will suffer. The American Standard Minimum Requirements for Sanitation[6] considers that "ready accessibility" has not been provided when an employee has to travel more than one floor-to-floor flight of stairs to or from a toilet facility. It is understandable that some minimum standard on the basis of distance must be set. However, the advent of complex automatic and remote controls and their inclusion in plant design may bring about modification of some distance standards.

In industries where the work clothes of the employee are exposed to contamination with poisonous, infectious, or irritating materials, separate storage for street and work clothes should be provided. Cash[33] suggests the following arrangement for such a "change house":

> A good arrangement is a room or building divided into two sections—a street clothes section and a work clothes section, with bathing and toilet facilities between. The street clothes section has an outside entrance and lockers for street clothes, toilets and wash basins or wash fountains, and changing facilities for supervisors. The work clothes section has rooms for work clothes, toilets and wash basins or wash fountains, showers, and laundry. Three connections between the street clothes section and the work clothes section are (*1*) through the supervisors' change room, (*2*) through the main shower room, and (*3*) a hall with "one way traffic doors" from street to work clothes sections.

In the mineral, petroleum, and allied industries the change house may be located at the entrance gate or near the parking lot to make it readily accessible. It may be a separate building connected to the working area by a covered walkway and should be constructed of fireproof or fire-resistant materials, properly heated, lighted, and ventilated to meet the general requirements of Section 4 of the American Standard Minimum Requirements for Sanitation.[6] The interior arrangement of the equipment and facilities in change houses and in locker and toilet rooms is not standardized, but is a matter of proper design to meet the space cost and other requirements of the individual plant.

The minimum facilities required for places of employment are set forth in the various state regulations of departments of labor and divisions of industrial hygiene. In addition, various industrial associations have established through industry-wide sanitation committees practice codes related to the particular industry. An example is the *Code of Recommended Practices for Industrial Housekeeping and Sanitation* of the American Foundrymen's Association.[34] The Association of Food Industry Sanitarians, in co-operation with the National

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[33] F. E. Cash, Suggested standards for change houses. Presented at American Public Health Association Annual Meeting, October, 1951.

[34] *Code of Recommended Practices for Industrial Housekeeping and Sanitation.* American Foundrymen's Association, Chicago, 1944.

Canners Association, has published a comprehensive manual, *Sanitation for the Food-Preservation Industries*.[35] For all places of employment minimum requirements for toilet facilities, washing facilities, change rooms, and retiring rooms for women are set forth in the American Standard Minimum Requirements for Sanitation.[6] Among the detailed requirements, this standard specifies the following:

Toilets

Water closets shall be provided for each sex according to the following table. The number to be provided for each sex shall in every case be based on the maximum number of persons of that sex employed at any one time at work on the premises for which the facilities are furnished. When persons other than employees are permitted to use the toilet facilities on the premises, a reasonable allowance shall be made for such other persons in estimating the minimum number of toilet facilities required.

Number of persons	Minimum number of facilities
1 to 9	1
10 to 24	2
25 to 49	3
50 to 74	4
75 to 100	5
Over 100	1 for each additional 30 persons

Where 10 or more are employed, urinals may be provided. One water closet less than the above specified number may be provided for males for each urinal, except that the number in such cases may not be reduced to less than $^2/_3$ of the number specified above. Two feet of trough urinal shall be considered as equivalent to one individual urinal.

In new installations, the minimum floor space allotted for water closets, lavatories, and urinals should be as follows:

	Minimum width (in.)	Minimum depth (in.)	Minimum room space per unit (sq. ft.)
Water closets	32	42	16
Lavatories	24	42	12
Urinals	24	42	12

It is suggested that in the absence of state or local building codes, the requirements of the American Standard Plumbing Code, ASA-A40.7-1949, or the latest revision thereof approved by the American Standards Association, Incorporated, be followed in the construction and installation of toilet facilities.

Chemical Closets and Privies

When chemical closets or privies are permitted, they shall be of a type approved by the health authorities having jurisdiction and shall be maintained in a sanitary condition. In the absence of specific regulations, construction and maintenance shall be in accordance with American Standard Specifications for the Sanitary Privy, Z4.3-1935 (Supplement 108 to Public Health Reports), or the latest revision thereof approved by the American Standards Association, Incorporated.

[35] *Sanitation for the Food Preservation Industries*. Association of Food Industry Sanitarians and National Canners Association, Berkeley, Calif.

Where more than two closets for each sex are needed, a water carriage disposal system should be installed in lieu of chemical closets or privies.

Washing Facilities

At least one lavatory (wash basin) with adequate hot and cold water, preferably from a combination supply fixture, shall be provided for every 20 employees (male or female) or portion thereof, up to 100 persons, and one lavatory (wash basin) for each additional 25 persons or portion thereof. Twenty-four inches of sink with individual faucet shall be considered as equal to one lavatory. In all instances, a suitable cleansing agent shall be provided at each wash place.

Where employees are exposed to skin contamination with poisonous, infectious, or irritating material, one lavatory supplied with hot and cold water, preferably from a combination supply fixture, shall be provided for every 5 employees.

One shower bath with ample supply of hot and cold water from one fixture shall be supplied for every 15 workers, or portion thereof, exposed to excessive heat or to skin contamination with poisonous, infectious, or irritating material.

Individual hand towels, or sections thereof, of cloth or paper shall be provided and proper receptacles or other sanitary means maintained for disposing of used towels. Other apparatus for drying the hands may be substituted for towels upon approval by the authorities having jurisdiction. The provision of a towel for general or common use shall be prohibited.

Retiring Rooms for Women

Where less than 10 women are employed and a rest room is not furnished, some equivalent space shall be provided which can be properly screened for privacy and made suitable for the use of women employees.

At least one couch or bed shall be provided in every place where more than 10 women are employed. The number of such beds or couches required shall be as follows:

10 to 100	1 bed
100 to 250	2 beds

1 additional bed for each additional 250 women employees.

A minimum of 60 sq. ft. per bed shall be provided.

In general, minimum standards for toilet facilities are delineated quite specifically as to their construction and provision for ease of cleaning. Barron[36] points out that, in some instances at least, the standard lavatories installed in washrooms fail to meet the need for ease of washing. The wash fountain with its foot pedal control, basin large enough to permit easy bathing of arms, face, and upper torso, free-flowing stream of thermostatically tempered water, and central cleansing dispenser offers a practical solution to the problem of providing good washing facilities. In addition, the wash fountain requires less floor space, initial installation is less complicated and costly, and it is maintained with greater ease. Experience with wash fountains in female washrooms indicates that they are acceptable there.

[36] J. L. Barron, Handwashing, difficult or easy?, *Modern Sanitation*, **6**, 23 (July, 1954).

VI. Maintenance of General Cleanliness of the Industrial Establishment

Housekeeping and plant cleanliness in their fullest sense imply not only the absence of clutter and debris in the working area and passageways, but also the maintenance of painted surfaces in a clean condition, the frequent removal of dust from lighting fixtures, and in general making the plant "a better place to work." The industrial plant that processes hazardous or potentially hazardous materials that cannot be prevented from escaping into the general atmosphere has a double responsibility to provide the utmost in housekeeping and plant cleanliness.

It is no longer sufficient to delegate responsibility for cleanliness of the plant and surroundings to a foreman or supervisor whose primary duties, interests, and training lie elsewhere. The complexity and cost of housekeeping machinery and supplies, the technical knowledge required for their proper and effective use, and the extensiveness of the workload make the establishment of a housekeeping department in large plants a virtual necessity. Working standards, schedules, and quality controls are also required in this routine plant operation. Additional evidence of the economic importance of this operation is the fact that fire insurance premiums are in part determined by the status of plant cleanliness.

VII. The Sanitary Engineer in Industry

The environmental factors described in this chapter are inherent in varying degrees in every industrial establishment. Those plants whose products are intended for human food may be placed in a special category since they have a paramount responsibility to protect their product from contaminants that endanger the health of the consumer. Because of this responsibility the role the sanitary engineer and sanitarian have to fulfill in such industries should be obvious to all. It is the second category of industry—the industry whose products are not intended for human food - which only recently has learned to utilize the sanitary engineer effectively. The recognition by industry of the great need to conserve the nation's water resources through effective control and treatment of industrial wastes, the desire to provide production and management personnel with safe food and potable water at all times, and the need for maintaining a sanitary working environment to protect the employee from those diseases that are not directly of occupational origin can be combined in a valuable service to industry. Most generally, the sanitary engineer is employed by industry to apply his knowledge to the solution of problems of industrial water supply and its corollary, liquid waste disposal. However, his engineering and public health skills are indeed more widely applicable in such areas as solid wastes disposal, food sanitation, insect and rodent control, and plant maintenance. Although the sanitary engineer may not be directly associated with the occupational health section of the industry, the roles filled by him and the industrial hygienist are directed toward the same end. The parallel may be further drawn by pointing out that just as the industrial hygienist aims to recognize hazardous working conditions in the design stage in order to eliminate them completely or make the application of control measures more effective, convenient, and economical, so the sanitary engineer in industry applies the same principle to the control of environmental factors other than those related to the occupation per se.

Many industries are too small to warrant the employment of a full-time sanitary engineer or sanitarian. The possibility of a number of industries co-operating in the provision of sanitary engineering services is worthy of consideration. In any event, state and local health department sanitary engineering personnel have a duty to co-operate with industry by providing such services as review of plans and general consultation on environmental health problems within industry. This may be accomplished either through the industrial hygiene division or, if none exists, directly with the sanitary engineering division of the health department.

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CHAPTER VI

The Mode of Entry and Action of Toxic Materials

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The toxicity of a material and the hygienic standard or threshold limit applying to its use are of considerable interest, but they must not be confused with the hazards of using the material. Gases may replace all of the air in the atmosphere while the amount of vapor in the atmosphere at any time is limited by the vapor pressure of the liquid or solid from which it arises. The amount of suspended particulate matter, for instance, dust, mist, or fume, in the atmosphere, however, is not limited by vapor pressure. There is also some evidence that particulates may absorb gases and vapors, thereby altering and in some instances increasing their physiological action. Gases and vapors of low solubility in water as well as those sorbed by particles of micron size tend to exert their action in the lower respiratory tract.

In order to plan the prevention of injury from toxic materials in industry it is essential that we have a clear understanding of how these materials enter the body, how they act therein, and how they are eliminated. In order better to understand these processes, we should understand respiration and circulation and their role in absorption and elimination. This in turn necessitates an understanding of the gas laws, with an ability to apply them to the solution of gases in liquids and, specifically, in the body fluids. We need also to know how different materials act upon the body and to understand the different types and degrees of physiological response.

I. Classification of Contaminants

The earth is surrounded by a gaseous atmosphere of rather fixed composition: 78.09 per cent nitrogen, 20.95 per cent oxygen, 0.93 per cent argon, 0.03 per cent carbon dioxide, insignificant amounts of neon, helium, and krypton, and traces of hydrogen, xenon, radioactive emanations, oxides of nitrogen, and ozone, with which may be mixed anywhere up to 5.0 per cent water vapor. Any of these gases in greater proportion than usual, or any other substance present in the atmosphere, may be regarded as a contaminant, or as atmospheric pollution. The possibilities of contamination are legion, but we may classify them according to their physical state, their chemical composition, or their physiological action.

A. PHYSICAL CLASSIFICATIONS

1. *Gases and Vapors*

While, strictly speaking, a gas is defined as a substance above its critical temperature and a vapor as the gaseous phase of a substance below its critical temperature, the term "gas" is usually applied to any material that is in the gaseous state at 25° C. and 760 mm. Hg pressure; and "vapor," to the gaseous phase of a substance ordinarily liquid or solid at 25° C. and 760 mm. Hg pressure. The usage distinction between gas and vapor is not sharp, however; for example, hydrogen cyanide, which boils at 26° C., is always referred to as a gas, while hydrogen chloride, which boils at −83.7° C. is sometimes referred to as an acid vapor.

2. *Particulate Matter*

a. Aerosol. A dispersion of solid or liquid particles of microscopic size in a gaseous medium: for instance, smoke, fog, and mist.

b. Dust. A loose term applied to solid particles predominantly larger than colloidal and capable of temporary suspension in air or other gases. Derivation from larger masses through the application of physical force is usually implied.

c. Fog. A loose term applied to visible aerosols in which the dispersed phase is liquid. Formation by condensation is implied.

d. Fume. Solid particles generated by condensation from the gaseous state, generally after volatilization from melted substances and often accompanied by a chemical reaction, such as oxidation. Popular usage sometimes includes any type of contaminant.

e. Mist. A loose term applied to dispersion of liquid particles many of which are large enough to be individually visible without visual aid.

f. Smog. A term derived from smoke and fog and applied to extensive atmospheric contamination by aerosols arising from a combination of natural and man-made sources.

g. Smoke. Small gas-borne particles resulting from incomplete combustion and consisting predominantly of carbon and other combustible materials.

B. CHEMICAL CLASSIFICATIONS

Chemical classifications are variously based upon the chemical composition of the air contaminants and may vary widely depending upon the aspect of the composition to be emphasized. The classification used in Volume II of this book is an example of chemical classification.

C. PHYSIOLOGICAL CLASSIFICATIONS

As has been pointed out by Henderson and Haggard,[1] the physiological classification of air contaminants is not entirely satisfactory because, with many gases and vapors, the type of physiological action depends upon concentration. For instance, a vapor at one concentration may exert its principal action as an anesthetic, while a lower concentration of the same vapor may, with no anesthetic effect, injure the nervous system, the hematopoietic system, or some visceral organ. Although it is frequently impossible to place a material in a single class correctly, a suggested physiological classification follows.

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[1] Y. Henderson and H. W. Haggard, *Noxious Gases* 2nd ed., Reinhold, New York, 1943

1. Irritants

Irritant materials are corrosive or vesicant in their action. They inflame moist or mucous surfaces. They have essentially the same effect upon animals as upon men, and the concentration factor is of far greater significance than the time, duration of exposure, factor. Some representative irritants are:

(*a*) Irritants affecting chiefly the upper respiratory tract: aldehydes (acetaldehyde, acrolein, formaldehyde, paraform), alkaline dusts and mists, ammonia, chromic acid, ethylene oxide, hydrogen chloride, hydrogen fluoride, sulfur dioxide, sulfur trioxide.

(*b*) Irritants affecting both the upper respiratory tract and lung tissues: bromine, chlorine, chlorine oxides, cyanogen bromide, cyanogen chloride, dimethyl sulfate, diethyl sulfate, fluorine, iodine, ozone, sulfur chlorides, phosphorus trichloride, and phosphorus pentachloride.

(*c*) Irritants affecting primarily the terminal respiratory passages and air sacs: arsenic trichloride, nitrogen dioxide and nitrogen tetroxide, and phosgene. (To the extent that their action frequently terminates in asphyxial death, lung irritants are related to the chemical asphyxiants.)

2. Asphyxiants

The asphyxiants exert their effects by interfering with the oxidation of the tissues. Their action is well understood and, in general, the response of human beings is similar to that of many animals, including dogs. This group can be subdivided into simple and chemical asphyxiants. Simple asphyxiants are physiologically inert gases that act principally by dilution of the atmospheric oxygen below the partial pressure required to maintain an oxygen saturation of the blood sufficient for normal tissue respiration. The chemical asphyxiants, on the other hand, through chemical action either prevent the blood from transporting oxygen from the lungs or prevent normal oxygenation of the tissues, even though the blood is well oxygenated. Examples of asphyxiants are:

(*a*) Simple asphyxiants: carbon dioxide, ethane, helium, hydrogen, methane, nitrogen, nitrous oxide.

(*b*) Chemical asphyxiants: carbon monoxide, which combines with hemoglobin; cyanogen, hydrogen cyanide, and nitriles, which inhibit tissue oxidation by combining with cellular catalysts; aniline, methyl aniline, dimethyl aniline, and toluidine, which form methemoglobin; nitrobenzene, which has the nitrite effect, forms methemoglobin, lowers blood pressure, disturbs and finally halts breathing; and hydrogen sulfide, which causes respiratory paralysis. (See also lung irritants.)

3. Anesthetics and Narcotics

This group exerts its principal action as simple anesthesia without serious systemic effects, and the members have a depressant action on the central nervous system governed by their partial pressure in the blood supply to the brain. The following examples are arranged in the order of their decreasing anesthetic action compared with other actions: (*a*) acetylene hydrocarbons (acetylene, allylene, crotonylene); (*b*) olefin hydrocarbons (ethylene to heptylene); (*c*) ethyl ether and isopropyl ether; (*d*) paraffin hydrocarbons (propane to decane); (*e*) aliphatic ketones (acetone to octanone); (*f*) aliphatic alcohols (ethyl, propyl, butyl, and amyl); (*g*) esters (not particularly anesthetic, but placed here for want of a better classification)—they hydrolyze in the body to organic acids and alcohols.

4. Systemic Poisons

(*a*) Materials that cause organic injury to one or more of the visceral organs: the majority of the halogenated hydrocarbons.

(*b*) Materials damaging the hematopoietic system: benzene, phenols, and, to some degree, toluene, xylene, and naphthalene.

(*c*) Nerve poisons: carbon disulfide, methyl alcohol, thiophene.

(*d*) Toxic metals: lead, mercury, cadmium, antimony, manganese, beryllium, etc.

(*e*) Toxic nonmetal inorganics: compounds of arsenic, phosphorus, selenium, and sulfur; fluorides.

5. Particulate Matter Other Than Systemic Poisons

(*a*) Fibrosis-producing dusts: silica, asbestos.

(*b*) Inert dusts: carborundum, carbon, emery.

(*c*) Dusts causing allergic reactions: pollen, wood, resins, and many other organic dusts.

(*d*) Irritants: acids, alkalies, fluorides, chromates.

(*e*) Bacteria and other microorganisms.

II. Respiration

A. MECHANICS OF RESPIRATION

During inspiration, air forced by atmospheric pressure enters the nasal openings, passes through the pharynx, larynx, trachea, bronchi and bronchioles through the terminal bronchioles, the respiratory bronchioles and alveolar ducts, into the air sacs or alveoli, filling the void created by involuntary muscular expansion of the thoracic cavity. Expiration may be either by muscular effort or by elastic contraction of lung tissue, but in quiet breathing contraction is thought to be entirely passive. The normal function of respiration is to supply atmospheric oxygen through the alveolar walls to the blood for distribution to the tissues and to remove carbon dioxide resulting from oxidation within the cells. The oxygen and carbon dioxide exchange in the tissues is sometimes referred to as tissue or internal respiration, as distinguished from the aeration of the lungs or external respiration.

B. LUNG STRUCTURE, VITAL CAPACITY, AND THE DEAD SPACE

The tracheobronchial tree as described by Miller[2] is supported by cartilage, the trachea being a series of open cartilaginous rings or crescents connected on the posterior side by bundles of muscle. The rings are joined to each other by a dense layer of connective tissue. The result is a rather rigid ribbed tube capable of some adjustment in diameter. This tube divides into the right and left main bronchi extending downward at approximately 20 degrees for the right, and 40 degrees for the left branch. The bronchi are further divided and subdivided into smaller and smaller bronchial passages. There is a muscular network essentially transverse to these passages, and as the passages decrease in diameter the cartilaginous rings become less complete, finally losing their cresent shape to become merely small plates of cartilage. As the cartilage decreases there is an increase in the proportion of muscular tissue. Cartilaginous support finally disappears toward the outer end of the bronchioles, where the diameter is about 0.5 mm. These terminal bronchioles connect with respiratory bronchioles which branch into alveolar ducts, terminating in the alveoli. These bronchioles range from 1.5 to 0.2 mm. in length and are about 0.2 to 0.4 mm. in diameter.

Normally the lungs fill about 80 per cent of the total chest cavity. An average man can inhale about $3^1/_2$ liters of air by forced effort after an ordinary exhalation. Likewise, he can forcibly exhale about 1 liter after an ordinary exhalation. The sum of these, about $4^1/_2$ liters, is called the vital capacity. There is in addition about 1 to $1^1/_2$ liters residual air which cannot be expelled by forced exhalation but remains in the lungs to aerate the blood during exhalation. Thus there is a total volume in excess of $5^1/_2$ liters, of which less than 10 per cent is used in normal breathing. The approximately 500 ml. of air inhaled and exhaled during normal respiration is called tidal air, and of this 500 ml. about 150 ml. is required to fill the tracheobronchial tree or anatomical dead space—that portion of the respiratory tract consisting of thick-walled passages through which no interchange of gases between blood and air can occur. During an ordinary 500 ml. inspiration, then, 150 ml. practically unaltered atmospheric air fills the dead space, while 350 ml. enters the alveoli and respiratory exchange area of the lungs.

[2] W. S. Miller, *The Lung*. Thomas, Springfield, Ill., 1937.

Then during expiration, alveolar air containing 5 to 6 per cent carbon dioxide and 12 to 14 per cent oxygen, is forced from the alveoli through the dead space, leaving this dead space filled with alveolar air. The first part of the exhalation is essentially atmospheric air and the last part alveolar air, with the mixture growing richer in alveolar air throughout expiration. Undiluted alveolar air can be obtained successfully only from air forcibly exhaled at the end of an ordinary respiration. Failure to consider this well-established fact can lead to serious errors in sampling expired air, as for instance in the determination of the radon content of the alveolar air. The maximum rate of physical activity that can be maintained by an individual is probably more dependent upon his maximum breathing capacity, minute ventilation, than upon lung volume. This minute ventilation is partially conditioned by frictional resistance along the air passages due to impediments, such as constrictions and abrupt changes in direction, or air passages merging at too great an angle.

C. REGULATION AND CONTROL OF RESPIRATION

The respiratory movements are regulated and controlled chemically as well as by the voluntary and involuntary nervous systems. Carbon dioxide acts as a stimulus to the respiratory center, and the CO_2 tension in the blood is by far the most significant factor of control. It is thought to act by raising the hydrogen-ion concentration of the respiratory center. Lactic acid resulting from strenuous exercise is thought to have a similar effect. Oxygen—or, rather, lack of it—is likewise a stimulus, but under normal conditions does not come into play because the partial pressure of oxygen in the alveolar air must fall markedly before the oxygen tension of the arterial blood is significantly affected. This is easily understood upon examination of the oxygen dissociation curve for blood, as is illustrated in Figure 1. Men with long experience in testing atmospheres in the holds

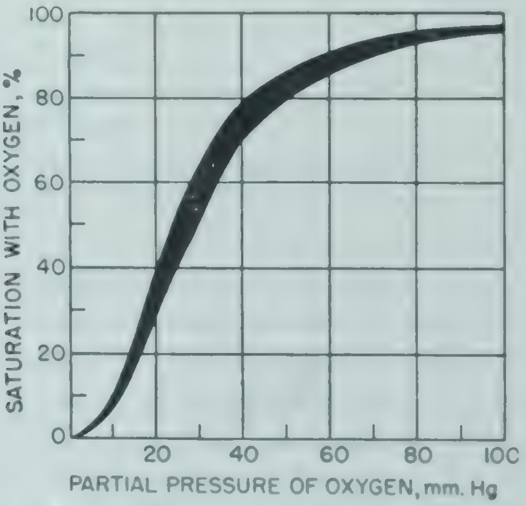

Figure 1. Dissociation curve of oxyhemoglobin for human blood expressed as the normal range of percentage of saturation with oxygen. (After Barcroft.)

of ships say that they can recognize atmospheres deficient in oxygen by this stimulating effect, but this is not recommended practice even for the well initiated because the margin between irrespirable atmospheres and those causing respiratory distress in the form of hyperpnea and dyspnea is too narrow. The suddenness of the onset of weakness and unconsciousness is so very marked that should a man enter an oxygen-deficient atmosphere by means of a ladder, the probability of his being able to remount the ladder unassisted, after becoming aware of distress, is not favorable.

The tension or partial pressure of oxygen in normal air is 20.95 per cent of an atmosphere, which equals 159.2 mm. Hg at sea level. Significant symptoms of distress do not occur until the percentage falls below 16 per cent, while unconsciousness may occur at concentrations below 11 per cent, and breathing soon stops if the oxygen falls below 6 per cent.

D. FUNCTION OF HEMOGLOBIN

The transportation of oxygen from the lungs to the cellular tissues is accomplished largely by means of the hemoglobin in the red cells of the blood. Likewise the carbon dioxide removed from the tissues is transported chiefly by the same agent. Each 100 ml. of arterial blood contains about 15 g. of hemoglobin, which combines with 19 or 20 ml. of oxygen. In blood that is in equilibrium with air at normal atmospheric pressure, about 1 per cent of the total oxygen is in solution in the plasma. Normal venous blood contains 12 to 14 ml. of oxygen per 100 ml. of blood, and about 1 per cent of this is dissolved in the plasma. For the return trip to the lungs the venous blood carries 55 to 60 volume per cent carbon dioxide and deposits about 10 per cent of this as it takes up its oxygen supply. The amount of carbon dioxide in simple solution is about 3 volume per cent in the venous blood and 2.5 volume per cent in the arterial blood. Since the blood in making its circuit flows through the capillaries of the lungs in approximately 1 second,[3] and through active tissue in a similar time, it is evident that mere solution of oxygen and carbon dioxide cannot account for the exchange of these gases, even though the equilibration in the lungs is highly efficient. The speed of exchange is due to the light combination of these gases with hemoglobin to form oxyhemoglobin and carbhemoglobin, respectively, as well as to the presence of catalysts in the red cells that play an important part in the oxygen and carbon dioxide exchange. Carbonic anhydrase is said by Best[3] enormously to increase in either direction the reversible chemical reaction $H_2CO_3 \rightleftharpoons CO_2 + H_2O$, while oxidation and reduction in the tissues are greatly accelerated by oxygen-activating catalysts or by dehydrogenases.

E. CIRCULATION AS A FACTOR, AND ITS REGULATION

Since the oxygen in the lungs cannot take part in the metabolic process until it has entered the blood stream and then been transported to the tissues, it is evident that the circulation rate is an important factor in respiration. The blood volume is usually slightly greater than the lung capacity. For a normal man it is approximately 6 to 7 liters.[3]

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[3] C. H. Best and N. B. Taylor, *The Physiological Basis of Medical Practice*. 6th ed., Williams & Wilkins, Baltimore, 1955.

The time required for a complete circuit of the blood varies with exercise, the part of the body supplied, and many other factors, but averages somewhat less than 1 minute. The normal heart stroke is about 60 to 70 ml., with a resting pulse of 68 to 72 per minute, giving a minute volume of 4 to 5 liters. Exercise can increase the heart stroke to 100 or 200 ml. and the pulse rate to 170 or 180. Environmental temperatures above 30° C. increase the minute volume 5 to 30 per cent. Digestion of food increases the basal minute volume by 30 to 40 per cent for about 3 hours. Emotional strain causes an increase of 15 to 25 per cent. pH changes have an effect, as do naturally occurring, as well as foreign, chemicals having a vasoconstrictor or vasodilator reaction. Also, just as the amount and content of the venous supply to the lungs play a major role in regulating the breathing required to keep the arterial blood constant, so does the circulation depend on breathing, and any retardation of breathing will be quickly followed by a change in circulation. Henderson[4,5] strikingly demonstrated the control of circulation by breathing when he showed that excessive pulmonary ventilation could induce failure of the circulation. The part played by respiration in the action of atmospheric contaminants upon the body will be discussed later.

III. Absorption, Distribution, and Elimination

A. MODES OF EXPRESSING CONCENTRATIONS

The extent of atmospheric contamination in the gaseous phase is frequently expressed as parts per million (p.p.m.), denoting units of volume in 1,000,000 volumes, and is usually corrected to 25° C. and 760 mm. Hg pressure. This is a convenient mode of expression and, for routine examinations of workroom atmospheres, the actual conditions are frequently not sufficiently removed from this standard to require temperature–pressure corrections. Since comparisons in p.p.m. are on a volume—hence molecular –basis they have no direct relation to the weight–volume expression of milligrams per liter occasionally used, especially in foreign technical publications. The milligrams per liter unit has the advantage of being more readily compared with existing pharmacological and dosage data, expressed as milligrams per kilogram of body weight. On the whole, however, the p.p.m. unit has proved much more convenient and expressive in industrial hygiene, where low concentrations of contaminants are the rule. Variations in the expression of parts by volume are: per cent by volume, parts per thousand, parts per ten thousand, parts per hundred thousand, parts per hundred million, and parts per billion. The excuse for employing so many units is the desire to

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[4] Y. Henderson, *Am. J. Physiol.*, **25**, 310 (1910).

[5] Y. Henderson and H. W. Haggard, *J. Biol. Chem.*, **33**, 355 (1918).

use small whole numbers. However, this multiplicity of units is confusing and might better be confined to not more than three units: per cent, parts per million, and parts per billion. Per cent by volume is generally used when the concentrations are on the order of 0.1 per cent or greater. Parts per million is a logical unit for concentrations ranging from 1,000 down to 1 or even 0.1 p.p.m. For concentrations less than 1 p.p.m., parts per billion (p.p.b.) appears to be the logical unit. One million p.p.b. = 1,000 p.p.m. = 0.1 per cent = a partial pressure of 0.76 mm. Hg at sea level. One gram mole of a perfect gas or vapor has a volume of 24.45 liters at 25° C. and a pressure of 760 mm. Hg. Therefore under these conditions:

$$1 \text{ p.p.m.} = \frac{\text{molecular weight}}{1000 \times 24.45} \text{ mg. per liter;}$$

and

$$1 \text{ mg. per liter} = \frac{24.45 \times 1000}{\text{molecular weight}} \text{ p.p.m.}$$

A conversion table for gases (p.p.m. to mg. per liter and mg. per liter to p.p.m.) is given on pages xvi–xvii. Another method of expressing gas concentrations is the partial pressure method, using the unit of the pressure exerted by one millimeter of mercury. This is convertible directly to per cent by volume by multiplying by 100 and dividing by the barometric pressure; or to p.p.m. by multiplying by 1,000,000 and dividing by the barometric pressure:

$$\frac{\text{Partial pressure of one constituent}}{\text{Total barometric pressure}} \times 1{,}000{,}000 = \text{p.p.m. of constituent}$$

When the contaminant is dispersed in the atmosphere in solid or liquid form, as a mist, dust, or fume, its concentration must be expressed either on a weight per volume basis or particles per volume basis. Liquids and toxic solids are usually expressed as milligrams per cubic meter, or per 10 cu. m. to approximate the maximum amount inhaled in one 8-hour day by a workman doing moderately heavy work. This standard was originally based on 20 liters per minute × 60 minutes × 8 hours = 9600 liters = 9.6 cu. m. Henderson and Haggard[1] estimate the average breathing rate to be 8 liters per minute or about 4 cu. m. per 8-hour day. Since not only the minute volume, but also retention, the physiological dead space, and other factors must be considered in computing daily systemic intake, the validity of the figure, 10 cu. m., is open to question. Those dusts that exert their effects largely within the lungs, rather than throughout the system as a whole, are usually counted microscopically and expressed as million particles per cubic foot of air. Outdoor air contaminants and stack effluents are frequently expressed as grams, milligrams, or micrograms per cubic meter, ounces per thousand cubic feet, pounds per thousand pounds of air, and grains per cubic foot. There is happily a trend toward the use of metric units because most data are collected in these units; but there is also justification for the use of English units because of existing data, especially specifications in such units for air-moving equipment. Conversion factors should always be provided (see the table on page xv). Expressions containing both English and metric units should not be used. The p.p.m. unit (weight to volume) used in water analysis (milligrams per liter) must not be confused with the p.p.m. (volume to volume) unit used in the analysis and expression of atmospheric constituents.

B. VOLUME-PRESSURE-TEMPERATURE RELATIONS

Boyle's law, which states that a perfect gas without change of temperature varies inversely in volume with the pressure to which it is subjected, and Charles' law, which states that at constant pressure the volume of a gas varies directly with the absolute temperature, are usually combined in one operation to convert observed gas or vapor volumes to normal conditions (25° C. and 760 mm. Hg pressure) as follows:

$$\text{Obs. vol.} \times \frac{298}{\text{obs. abs. temp. (°C.)}} \times \frac{\text{obs. bar. pres. (mm. Hg)}}{760} = \text{vol. at normal conditions}$$

This formula may be used, of course, to convert from any observed temperature and pressure to any desired temperature and pressure by substituting the proper values for the normal condition values as given. These industrial hygiene "normal conditions" are not sufficiently different from the "standard air" used in air conditioning and ventilation work (70° F. and 29.92 inches Hg. pressure) to require correction factors in most instances. Likewise these "normals" are sufficiently close to the temperatures and pressures of most occupied spaces that usually no correction is required in industrial hygiene work. The "Standard Temperature and Pressure" used by chemists, however (0° C. and 760 mm.), is sufficiently different (9 per cent) to introduce significant error unless temperature corrections for air volumes are made.

1. *Partial Pressures*

Each gas in a mixture exerts a pressure in direct proportion to its per cent by volume. In a sample of dry air, for example, at sea level the percentage composition and partial pressures are:

$$\text{Oxygen: } 20.95\% \times 760 \text{ mm.} = 159.22 \text{ mm. p.p.}$$

$$\text{Nitrogen, carbon dioxide, and inert gases: } 79.05\% \times 760 \text{ mm.} = 600.78 \text{ mm. p.p.}$$

If, without change in barometric pressure, this air should become humidified to the extent of 50 per cent relative humidity at 25° C., the composition would be altered as follows. Water vapor, 11.88 mm. partial pressure, would appear in the mixture, and since the total pressure does not change, the composition of the atmosphere becomes:

$$\text{Water vapor} = 11.88 \text{ mm. p.p.}$$
$$\text{Oxygen: } 20.95\% \times (760 - 11.88) \text{ mm.} = 156.73 \text{ mm. p.p.}$$
$$\text{Nitrogen, etc.: } 79.05\% \times (760 - 11.88) \text{ mm.} = 591.39 \text{ mm. p.p.}$$

Should a sample of this 50 per cent humidified air be transported to a higher altitude and opened for analysis, the partial pressures would decrease but the percentage composition would remain the same. At 750 mm. barometric pressure, for instance, this humidified air would have the partial pressure composition, as follows:

$$\text{Water vapor} = \frac{750}{760} \times 11.88 \text{ mm.} = 11.72 \text{ mm. p.p.}$$
$$\text{Oxygen: } 20.95\% \times (750 - 11.72) \text{ mm.} = 154.67 \text{ mm. p.p.}$$
$$\text{Nitrogen, etc.: } 79.05\% \times (750 - 11.72) \text{ mm.} = 583.61 \text{ mm. p.p.}$$

Gases are ordinarily reported on a dry basis, but variations in volume due to temperature, pressure, and water vapor changes may be computed by the formula:

$$V_1 = \frac{V_2(P_2 - W_2)(273 + T_1)}{(P_1 - W_1)(273 + T_2)}$$

where V_2 is the observed volume of gas at the observed temperature T_2; V_1 is the calculated volume of gas at temperature T_1; temperatures T_1 and T_2 are in degrees Centigrade; W_2 and W_1 are mm. Hg vapor tension of water at observed and calculated conditions; and P_2 and P_1 mm. Hg are the observed and the calculated barometric pressures, respectively. Air and vapors inhaled into the lungs are rapidly saturated with water vapor at body temperature to approach a partial pressure of 47 mm. Hg and, in computing the partial pressure of any vapor in alveolar air, this partial pressure of water must be considered.

C. ROLE OF SOLUBILITY IN ABSORPTION OF GASES AND VAPORS

1. Solubility Coefficient

Any gas confined in contact with a liquid dissolves at the surface of the liquid and enters the liquid until its partial pressure in the vapor phase above the liquid is in equilibrium with the gas dissolved in the liquid, that is, the rates of its dissolving and evaporating have become equal. The speed with which equilibrium is reached is a function of the solubility and the relationship of contact surface to volume of liquid—the greater the proportion of surface area, and the lower the solubility, the sooner equilibrium will be reached. At the same time the liquid vaporizes into the space above it until its partial pressure in the atmosphere is in equilibrium with its evaporation pressure in the liquid phase. Henry's law, *the* *concentration of a gas that will dissolve in a liquid is directly proportional to its concentration in the free space above the liquid*, may be expressed as $C_1/C_2 = K$, where C_1 and C_2 are the molar concentrations of the gas in the liquid and vapor phases, respectively, and K is the solubility coefficient. This coefficient is different for each vapor, each liquid, and each temperature.

Henderson and Haggard[1] have proposed that this law be expressed in a more convenient form when applied to the absorption of gases through the lungs into the blood. They suggest $C/C_1 = D$, where D is the coefficient of distribution, C is the concentration in the fluid phase (blood), and C_1 is the concentration in the vapor phase in alveolar air, both concentrations to be expressed on a weight per volume basis (milligrams per liter). This form of the law is particularly convenient for the purpose intended, and it is to be hoped that additional data will be collected to establish the coefficient of distribution of more gases and vapors between the atmosphere and the circulating blood. For a miscible or highly soluble material the coefficient of distribution cannot be approximated by calculation, but for a less readily soluble vapor it can be approximated from its vapor pressure and solubility at body temperature, 37° C. The coefficient of distribution is constant for the same vapor and liquid at any given temperature regardless of the concentration of vapor in the atmosphere.

TABLE 1

Distribution Coefficients

Solvent	Coefficient of distribution[a]	Ref. no.
Methyl alcohol	1700	1
Ethyl alcohol	1300	1
Isoamyl alcohol	836	6
Primary *n*-amyl alcohol	804	6
Secondary isoamyl alcohol	550	6
Acetone	330	7
Methyl *n*-propyl ketone	167	6
Diethyl ketone	157	6
Methyl isopropyl ketone	101	6
Ethyl ether	15	1
Benzene	6.58[b]	8
Carbon disulfide	5	9

[a] The coefficient of distribution here is the ratio of milligrams of solvent per liter of blood to milligrams of solvent per liter of alveolar air.

[b] Based upon room air rather than alveolar air.

The coefficient is known for the solubility of relatively few vapors and gases in blood at body temperature, this being a field that has been insufficiently explored

[6] H. W. Haggard, D. P. Miller, and L. A. Greenberg, *J. Ind. Hyg. Toxicol.*, **27**, 1 (1945).

[7] A. P. Briggs and P. A. Schaffer, *J. Biol. Chem.*, **48**, 413 (1921).

[8] H. H. Schrenk, W. P. Yant, S. J. Pearce, F. A. Patty, and R. R. Sayers, *J. Ind. Hyg. Toxicol.*, **23**, 20 (1941).

in toxicity studies. It is to be hoped that in the future such studies will include the partial pressure of the vapor or gas under observation in alveolar air, and in the body fluids, at time intervals during accumulation and elimination of vapors, as well as at equilibrium. In computing a coefficient of distribution from room-air vapor concentration data, corrections for changes in temperature and partial pressure of water vapor should be made if comparisons are desired with coefficients based upon alveolar air, because alveolar air approaches saturation with water vapor at 37° C. (47 mm. Hg partial pressure). Some of the coefficients that have been established are given in Table 1.

2. Body Saturation

From the foregoing it is evident that any gas or vapor in the air we breathe tends to pass through the lungs into the blood stream and to be distributed throughout the body. The respiratory tissue in the lungs, which has been estimated to have a surface area of about 55 sq. meters, acts as the exchange surface between blood and air. The blood in the capillaries is said to be separated from the air in the alveoli by two membranes of the utmost delicacy, perhaps only one cell in thickness, so it becomes evident that equilibrium between the blood in the lungs and the alveolar air is reached rapidly. The accumulation of the foreign gas or vapor in the body depends upon a number of factors: concentration in the air, the solubility of the material in the blood and tissues, the length of exposure, the rate of breathing, the rate of circulation, whether the material is reactive, and others.

If a gas is very soluble in the blood, saturation of the body is slow (requiring days), is largely dependent upon the ventilation of the lungs, and is only slightly influenced by changes in circulation; whereas with a very slightly soluble gas, such as nitrogen, saturation is very rapid (being nearly complete within a few minutes), is chiefly dependent upon the rate of circulation, and is little influenced by the rate of breathing. With gases and vapors that are freely soluble in water and nonreactive, or only slowly reactive, in the body, such as acetone and methanol, the absorption and distribution throughout the body are dependent upon the water content of the tissues. Although the fat-soluble vapors may be transported chiefly by the aqueous content of the blood, they tend to concentrate in the fatty tissues. With any nonreactive vapors, although the blood and tissue concentrations, short of equilibrium, are proportional to the vapor concentration and functions of the time of exposure, the rate of saturation is, with constant circulation and breathing, a relation peculiar to each vapor and independent of the concentration of the vapor. In other words, the same time is required for the same vapor to reach a given percentage saturation of the body, regardless of the concentration of the vapor in the atmosphere breathed.

It is not practical to speak of the exact time required for complete saturation, as this is a variable and too indefinite. It is, however, practical to state a time of some percentage saturation such as 50, 60, 70, 80, or even 90 per cent of saturation, but past this point the absorption curve for a gas or vapor of low reactivity becomes rather flat. With a relatively water-insoluble vapor such as benzene, blood saturation occurs so rapidly that even the venous blood may reach 70 to 80 per cent of saturation within 30 minutes, yet relatively complete saturation may require as much as 2 or 3 days. This can be explained by the fact that the fatty tissue, which has the greater affinity for benzene, removes and stores the benzene carried by the blood, but this fatty tissue has in many instances a very meager blood supply and therefore requires a longer period to attain equilibrium.

Methanol is typical of vapors highly soluble in water. About 24 hours inhalation of this vapor is required before the blood is 70 per cent saturated (about 50 times as long as for a similar percentage saturation with benzene), yet relatively complete saturation here requires little longer than with benzene, the difference being that the fatty tissues with their smaller blood supply are not a reservoir for methanol, and distribution throughout the body at equilibrium is directly proportional to the water content of each tissue. Both benzene and methanol are examples of very slightly reactive vapors.

Carbon disulfide, approximately 90 per cent of which has been found to be metabolized, may be cited as an example of a moderately reactive, relatively water-insoluble vapor. McKee and associates[9] have reported upon the blood saturation with carbon disulfide in inhalation exposures of dogs. From its physical and chemical properties, carbon disulfide would be expected to have an absorption curve resembling that for benzene except for the effect of a higher rate of metabolism, and McKee's data indicate that this is the case. If the points on his graph for the blood saturation of a dog breathing 50 p.p.m. carbon disulfide are connected by an exponential curve, the data indicate a saturation of around 90 per cent at the end of a 3½-hour exposure. The coefficient of distribution of CS_2 between blood and room air at this percentage saturation was 4.3 on a milligrams per liter basis.[10] If this were corrected for alveolar air temperature and humidity, the value at equilibrium would be approximately 5. Desaturation was rapid and, for single exposures, more or less complete within 2 to 6 hours. This is similar to the desaturation curve for benzene. During accumulation or absorption the arterial blood is saturated to a higher degree than venous blood, while at equilibrium or saturation the concentration is the same in each, and during elimination the concentration of benzene in the arterial blood is lower.

The difference in vapor concentration between arterial and venous blood is dependent upon the solubility or coefficient of distribution of the particular vapor. With a very soluble vapor the difference is negligible, while with a slightly soluble vapor, such as benzene, the difference is marked, and during accumulation the arterial blood, once the lungs are filled with vapor by the first few inhalations, is equilibrated with air only slightly less in concentration of vapor than the air inhaled. In other words, the blood passing through the lungs is not sufficient to absorb an appreciable percentage of the vapor from the alveolar air. This has an important bearing on brief exposures to high concentrations of slightly soluble vapors. The arterial blood supply to the brain is large: therefore, brief exposures to high concentrations of anesthetic gases or vapors of low solubility produce rapid effects even though the degree of saturation of the body is very low. The administration of ether is a good example of this point. Moderate concentrations may be given that will induce unconsciousness after ½ hour or more and the effects will be somewhat prolonged, or concentrations may be given sufficiently high to induce unconsciousness quickly and have recovery occur shortly after removal from exposure, providing the exposure has not been prolonged. This also has a practical bearing in degreasing work where a short exposure to high concentrations of trichloroethylene, or another similar solvent, may not materially raise general body concentration but may induce anesthesia. It is therefore important to know peak as well as average vapor concentrations.

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[9] R. W. McKee, C. Kiper, J. H. Fountain, A. M. Riskin, and P. Drinker, *J. Am. Med. Assoc.*, **122**, 217 (1943).

[10] R. W. McKee, private communication.

The curves in Figure 2 illustrate the differences in rate of absorption by inhalation and in approach to equilibrium in the circulating blood for different classes of gases and vapors. Nitrogen, nonreactive and slightly soluble, but with some specific affinity, approaches equilibrium rapidly (see also page 588). Carbon disulfide, moderately reactive and slightly soluble, approaches saturation rapidly, but data are lacking on the period of complete saturation. Benzene, very slightly reactive and slightly soluble, reaches 70 per cent saturation rapidly but does not attain complete equilibrium even after a period of 3 days. Methanol, a slightly reactive, highly soluble vapor, gradually approaches saturation, requiring about 24 hours for 70 per cent saturation and about 5 days for essentially complete saturation. Ethanol (not shown) attains saturation slightly more slowly than does methanol because it is metabolized fairly rapidly.

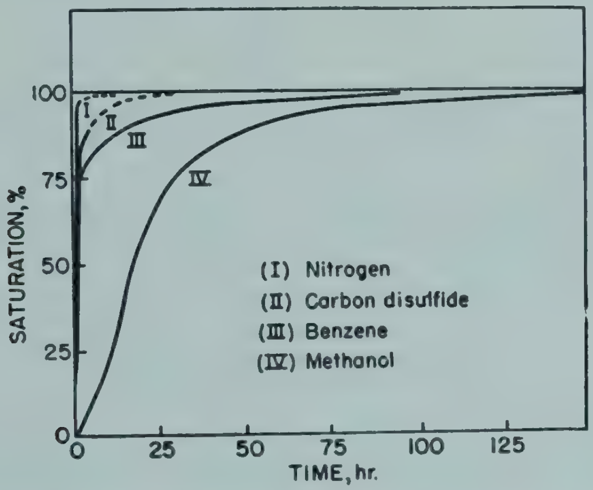

Figure 2. Curves illustrating the absorption of some representative gases and vapors into the blood of living dogs.

Figure 3 illustrates the relative rates of elimination for benzene after exposures for varying lengths of time. These curves indicate that the more severe the exposure to benzene, especially as regards the time factor, the more slowly is it eliminated from fatty reservoirs.

Figure 4 pictures the elimination of carbon disulfide after a brief single exposure to a low concentration, as well as typical elimination curves for ethanol and for methanol. Ethanol is more readily eliminated than methanol because rapid oxidation augments the elimination by expired air, while, as has been pointed out by Haggard and Greenberg,[11] over 70 per cent of the methyl alcohol is eliminated in the expired air.

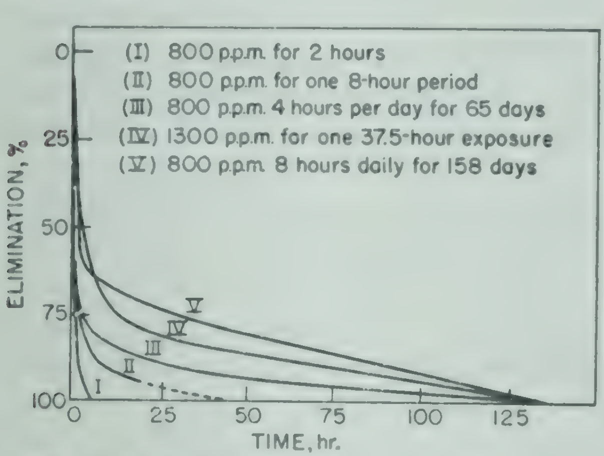

Figure 3. Curves illustrating the elimination of benzene from the blood of dogs after varying degrees of inhalation exposures.

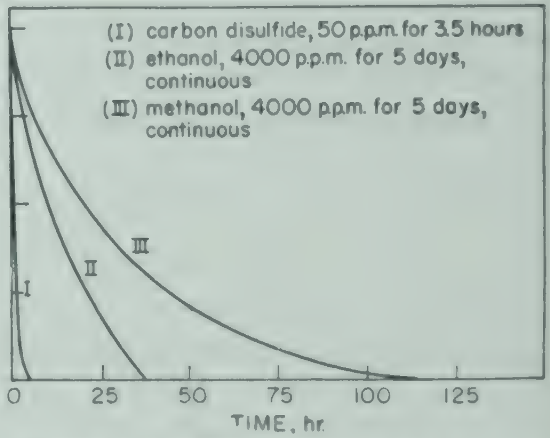

Figure 4. Curves illustrating the elimination of carbon disulfide, methyl alcohol, and ethyl alcohol from the blood of dogs after inhalation exposures.

3. *Effect of Intermittent Exposures*

What is the effect of repeated 8-hour exposures, each followed by a 16-hour period in uncontaminated air? Dogs have been so exposed to 500 p.p.m. methanol.[12] Absorption ranged from 10 to 20 per cent of saturation in the 8-hour period, and was followed by 50 to 100 per cent desaturation. This resulted in erratic pictures in which some animals gradually accumulated methanol to the extent of 52 per cent of saturation for the particular air concentration (52 per cent of the amount that could accumulate from a continuous exposure). From this high degree of saturation they gradually excreted until they again reached a low level of less than 20 per cent of saturation. Exercise or increased activity greatly speeded the change in either direction, but appeared to have no definite effect upon the direction.

In intermittent exposures to 800 p.p.m. benzene, the blood of dogs exposed 2 hours per day reached an average of about 60 per cent of saturation at the end of exposure, and the animals eliminated 82 per cent of this during the ensuing 22 hours. With a 4-hour daily exposure, the blood reached about 85 per cent saturation and the animals eliminated an average of 85 per cent of this within the following 20 hours. With a daily exposure of 8 hours, the blood reached an average saturation of 92 per cent, while elimination in the ensuing 16 hours was only 76 per cent of this. This frequently resulted in the animals apparently reaching complete saturation, from which high level they would again recede.

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[11] H. W. Haggard and L. A. Greenberg, *J. Pharmacol.*, **66**, 479 (1939).

[12] R. R. Sayers, W. P. Yant, H. H. Schrenk, J. Chornyak, S. J. Pearce, F. A. Patty, and J. G. Linn, *U. S. Bur. Mines, Rept. Invest.* No. **3617**, 1942.

With a highly water-soluble vapor, methanol, we see that from daily 8-hour exposures the vapor may accumulate over a period of time to as much as five times the amount resulting from a single 8-hour exposure, but it never reached more than about half the amount that could result from a continuous exposure, which is a function of the coefficient of distribution for that particular vapor. With a water-insoluble vapor such as benzene, however, there is relatively little accumulation, and the concentration of benzene in the blood is largely proportional to the concentration just having been inhaled at any time.

4. Relative Concentrations of Vapor in Blood, Tissues, and Expired Air

We have seen how the concentration of a vapor in the blood is controlled by the concentration of vapor in the inspired air, the length of exposure, and the solubility of the vapor in blood. Let us consider the concentrations of vapor in the tissues, in the body fluids other than blood, and in the expired air and how they are controlled. Henderson and Haggard[1] state that the concentration of any vapor in the urine is regulated by the concentration in the arterial blood passing through the kidney at the moment of secretion, differs from the concentration in the blood only by the ratio of solubilities of the vapor in the two fluids (approximately 1 : 1 for most vapors), and is a composite of the varying concentrations over the period during which it is secreted. This relation would be expected from the standpoint of physics and appears to hold true for several vapors, but the concentration of benzene in the urine averaged 20 times that in the blood.[8] This concentration has not been explained and certainly cannot be on the basis of the ratio of solubilities of benzene in blood and in urine, but would seem to indicate that the kidneys have the power to extract benzene from the blood in circulation.

For the tissues in general, the relative amounts of a vapor they contain at equilibrium are directly proportional to the solubility of the vapor in the various tissues, but tissues with the greater blood supply and lower solvent capacity saturate, or reach equilibrium, before the tissues of higher solvent capacity and lower blood supply. Likewise these same tissues with the greater blood supply and lower solvent capacity desaturate more rapidly.

The concentration of vapor in the alveolar air during accumulation, equilibrium, or desaturation regulates the concentration of vapor in the arterial blood leaving the lungs at the moment and therefore can be used as an indication of arterial blood concentration. At complete saturation the vapor concentration in the alveolar air is the same as that in the room air, with due correction for temperature and humidity. With the more soluble vapors, alveolar air concentration, at any point during accumulation, may be used to estimate the average room-air concentration, given the length of exposure, the saturation curve for the particular vapor, and its coefficient of distribution. An interesting variation, of much practical usefulness, is met in the case of radon: its concentration in the alveolar air may be used as an indication of radium storage or deposition, providing sufficient time has elapsed for relatively complete desaturation (8 hours or more after the end of an inhalation exposure).

The physical laws governing the rate of gas exchange between the blood and the respired atmosphere are the basis of a proposed method[13] for measuring pulmonary functional capacity in terms of lung ventilation, gas transfer by diffusion across the alveolar wall, and pulmonary blood flow. The authors suggest possibilities of determining the nature and magnitude of respiratory impairment.

D. DUSTS AND FUMES

1. The Absorption of Particulate Matter

Dusts, fumes, and smokes represent solid particlulate matter differing in quality, form, and particle size. The process of their accumulation, distribution, and elimination is much more complicated than the same process with gases. Brown[14] showed that with a number of dusts having a particle size range of 0.25 to 6.0 μ, approximately 55 per cent of the inhaled dust was retained by men. The extremes of retention reported, however, ranged from 15 to 95 per cent. Retention was found to be inversely proportional to the rate of respiration and minute ventilation for rates below 20 inhalations per minute, with no apparent change above 20. Retention was directly proportional to the size of particles or their aggregates, to density, and to wettability. Of this retained dust, a part is retained in the nasal filter and part by contact with wet surfaces in the respiratory passages, while some reaches the respiratory tissues. The upper respiratory passages are subject to brief periods of low velocity, or static air, between alternately directed flows of rather high velocity air. Because of sharp changes in direction, some dust, especially the larger particles, 5 to 20 μ in diameter, is impinged and arrested in these passages by contact with moist surfaces. In the alveoli the air must necessarily be static or moving slowly during respiratory movements, so that ample opportunity is presented for settling and for contact with the moist alveolar walls. If particles are caught before they enter the alveoli, they are continually swept toward the mouth by the ciliated epithelium,[3] which extends from the lower pharynx to the respiratory bronchioles. These ciliated cells are abundant in the trachea, and even more abundant in the large bronchioles, but are sparse in the respiratory bronchioles, and absent in the alveoli. The motions of the cilia are wavelike and their efficiency

[13] T. F. Hatch and K. M. Cook, *A.M.A. Arch. Ind. Health*, **11**, 142 (1955).

[14] C. E. Brown, *J. Ind. Hyg. Toxicol.*, **13**, 293 (1931).

in propelling mucous and foreign material toward the oral cavity is of a high order. The individual cilium moves toward its goal with whiplike motion, then slowly resumes its former position. It is evident, then, that dust particles trapped anywhere short of the alveolar ducts are subject to removal from the lungs through ciliary action. Upon arrival at the oral cavity they are expectorated or swallowed. Dust particles (silica) reaching and remaining in the alveoli are believed to be largely limited to the sizes ranging between 3 and 0.1 μ,[15] 3 being the largest to arrive at the alveoli in significant quantities. The majority of particles below 0.1 μ are thought to be too small to be trapped in the alveoli and are exhaled much the same as is an undissolved gas. The particles caught in the alveoli may be absorbed through the alveolar wall, or they may be engulfed in phagocyte cells and be carried into the blood capillaries, or enter the lymphatics and be concentrated at the tracheobronchial lymph nodes. Particles of silica 1 μ and under are the most active and dangerous, not only in their ability to remain suspended in the air, but especially in their activity in tissue.[16]

2. *Action of Suspended Particulate Matter*

The toxic dusts may dissolve and enter the circulation by absorption from the respiratory tract, or they may be absorbed after being swallowed. The action of these is discussed under the material involved. "Pneumoconiosis"-producing dusts may exert their effects after lodging in the alveoli. Other particulate matter may cause allergic reactions or, in the case of disease germs, infections. The possibility of the sorption of gases and vapors by particulate matter should not be overlooked as a source of significant exposure of the respiratory tract to these gases and vapors although they may not be present in significant concentrations in the *gaseous* environment. Also, it has been demonstrated that the normal locus of action of water-soluble gases may be transferred from the upper to the lower respiratory tract through sorption on particles, thereby increasing their physiological effect. Conversely, when gases less soluble in water, such as nitrogen oxides, phosgene, and ozone, are mixed with aerosols, their effects may be lessened because of sorption.[17] For a complete discussion of the role of dusts and the evaluation of disability arising therefrom see Chapter XII.

E. MISTS

Mists may be inhaled to reach all parts of the lungs and from there may be absorbed. Of a slightly volatile material, concentrations far above those possible from partial pressures of the gaseous phase at room temperature may be encountered. For that reason a solvent, the vapors of which may be considered harmless at ordinary temperatures, can be very dangerous as a mist.

[15] L. U. Gardner, *Ind. Med.*, **9,** 45 (1940).

[16] B. D. Tebbins, R. Z. Schulz, and P. Drinker, *J. Ind. Hyg. Toxicol.*, **27,** 199 (1945).

[17] C. W. LaBelle, J. E. Long, and E. E. Christofano, *A.M.A. Arch. Ind. Health*, **11,** 297 (1955).

F. OTHER MEANS OF ABSORPTION

1. Ingestion

Ingestion of toxic materials has been mentioned above as resulting from inhalation. It may also result from many other sources, such as contaminated food, tobacco, or beverages, or from putting fingers or other contaminated objects into the mouth, or from licking the lips. Compared with inhalation, ingestion plays a minor role in the absorption of most toxic materials in industry. However, progressive companies realize that occupational diseases can occur from the careless use of contaminated workrooms as a place in which to eat lunches—all too often without previously washing the hands (cf. also page 130).

2. Absorption through the Skin

Many gaseous and liquid materials are absorbed to a limited extent through the intact skin by way of the air spaces in the hair follicle to the sebaceous glands and the gland cells. Similarly, according to Rothman,[18] any substance may, through the sweat gland ducts, reach the secretory surface of the sweat gland cells after having passed the straight and the convoluted part of the ducts.

Most electrolytes and water do not penetrate the skin in significant amounts. Alkaloids, phenols, oxalic and salicylic acids and esters, lead acetate, and lead oleate are absorbed in appreciable amounts. Salts of lead, tin, copper, arsenic, bismuth, antimony, and mercury are said to penetrate by combining with the fatty acid radical of the sebum. Ammoniated mercury, however, is said not to be absorbed through the skin as such.[18] Nicotine, strychnine, and opium are absorbed readily, but their salts are not. Slight amounts of hydrogen sulfide and rapidly dangerous amounts of hydrogen cyanide may be absorbed from contaminated air. Nitrobenzene, dinitrobenzene, nitrotoluene, dinitrotoluene, (probably) trinitrotoluene, aniline, dimethylaniline, and nitroglycerin are readily absorbed from skin contact with these materials or their solutions. Hodge and Sterner[19] have shown that triorthocresyl phosphate is absorbed through the skin. Alcohols, aldehydes, and acetone are said to be readily absorbed, but from a practical viewpoint there seems to be little significant hazard from this source. Benzene, toluene, xylene, the chlorinated hydrocarbons, and other fat solvents are absorbed to a degree, but the quantities of these materials accumulated in the body in this manner are probably not of a significant order, although tetrachloroethane and other unusually toxic solvents may be exceptions to this statement. Absorption through lesions of the epidermis is much more rapid than through the intact skin.

IV. Standards of Physiological Response

In order to facilitate the comparison of data on the physiological response to the inhalation of atmospheric contaminants, many investigators have tabulated their data in degrees of response such as the following:

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[18] S. Rothman, *J. Lab. Clin. Med.*, **28**, 1305 (1943).

[19] H. C. Hodge and J. H. Sterner, *J. Pharmacol.*, **79**, 225 (1943).

Amount producing detectable or other degree of odor.
Amount producing detectable or other degree of irritation.
Maximum amount for repeated daily 8-hour exposures without injury.
Maximum amount for a single 8-hour exposure without serious disturbance.
Maximum amount for a single 1-hour exposure without serious disturbance.
Amount dangerous to life within several (4 to 8) hours.
Amount dangerous to life within $^1/_2$ to 1 hour.
Amount causing death within a few minutes.

Levels set for industrial practice have been variously labeled as threshold limits, maximum safe concentration, maximum allowable concentration, toxic limit, maximum permissible concentration, and maximum safe practice. What is, of course, the most desired value is the maximum concentration to which an individual may be exposed throughout his or her working day, for an indefinite period of time, without suffering any ill effects. Unfortunately this has been established satisfactorily for extremely few single substances. The human body is fortified with a defense, or detoxication, mechanism able to cope with all toxic materials in amounts below a certain level, called the threshold of intoxication. So long as this threshold of daily intake is not exceeded, there are no harmful effects, but as soon as this level is exceeded, injurious effects result. This level is not a definite and fixed point for any material, and it may vary not only with individuals, but also with bodily conditions of the same individual. There are many degrees or shades of toxicity among the materials encountered in industry, as, for instance, the volatile solvents. All of these are toxic if absorbed into the system in excess, their toxicity being a matter of degree, and none of them meriting the classification "nontoxic." How are we to set permissible or safe standards of air contamination for industry?

With very few exceptions all of our so-called "safe" limits are educated guesses. At their best they are estimates rather than actual safe limits. They are limits set after careful consideration of available toxicity data, largely obtained from exposure of animals, which further research or experience may or may not substantiate. Why, then, pretend that we know the maximum safe limit unless, as is true for carbon monoxide and other asphyxiants, lead, mercury, and possibly a few other materials, we have the data to establish the point? Even with the asphyxiants we perhaps are not positive of the effects of prolonged inhalation of concentrations too low to cause unconsciousness, and regarding the safe limit for lead, some evidence points to a need for specifying the physical state and chemical combination of the lead. It seems logical that we should, as a guide to the uninitiated, and a check upon the alarmist, and possibly the unscrupulous, without undue delay, set suggested maximum concentrations for materials as soon as, if not before, they attain industrial importance. We should call them hygienic standards, recommended good practice, tentative threshold limits, or suggested maximum concentration standards until we learn through experience, or research, the true maximum safe limit, and then, if necessary, change our standards accordingly.

V. Standards for Permissible Atmospheric Contamination and How They Are Set

Our present standards of practice regarding atmospheric contaminants are very helpful bench marks, as long as we regard them for what they are and do not try to set them up as absolute safe limits to be regarded as established facts comparable to, or in the same class with, flammable limits, flash points, or other properties that can be determined accurately. Rather, the idea should be fostered that the limits are flexible and are to be adjusted to conform with any new, properly weighted, evidence of facts regarding physiological effects. It must also be remembered that just as all of us are subject to occasional ill health regardless of our work environment, so are we at one time more easily affected by foreign materials than at another. There are probably too many uncontrollable factors for us to set a positively safe limit, applying to all people at all times, and still have the limit appreciably different from that of pure air. No matter how carefully our standards are established, if they are maintained at a level compatible with industrial practice, there may be occasional ill health in the especially susceptible individual. We shall always need periodic medical examinations by thorough and competent physicians.

The United States Public Health Service has been the outstanding contributor to our knowledge of maximum permissible limits for atmospheric contaminants, and some of the states have co-operated in the toxicological and chemical studies required to establish such limits. The United States Bureau of Mines, the United States Department of Labor, and a few universities and other schools of higher learning, as well as private research organizations, have added to the store of information.

Some of the states have set up "safe" standards of their own, some of which have developed into safe practice codes enforceable by law, but for the most part they have been restricted to advisory standards. A survey conducted by the author in 1943, including thirty-four states, revealed a wide range of figures adopted by these states as maximum safe concentrations. This wide variation indicated the need for a central advisory body, whether it be the United States Public Health Service, the American Standards Association, the American Industrial Hygiene Association, the American Conference of Governmental Industrial Hygienists, or some other qualified and representative body, to take the initiative in establishing permissible concentrations. More recently several states have adopted the recommendations of the Committee on Threshold Limits of the American Conference of Governmental Industrial Hygienists. This group reviews the information available to them and publishes yearly a list of "Threshold Limit Values and Tentative Threshold Limit Values." Even though this list may have several shortcomings.

it is widely regarded as the most reliable information on permissible contamination of the indoor environment and, therefore, serves a very useful purpose. The 1957 report of the above committee is reproduced here in its entirety.

Threshold Limit Values for 1957[20]

Adopted at the Nineteenth Annual Meeting of the American Conference of Government Industrial Hygienists, St. Louis, April 20–23, 1957

Values are given in the following tabulation for the maximum average atmospheric concentration of contaminants to which workers may be exposed for an eight-hour working day without injury to health.

These values are based on the best available information from industrial experience, from experimental studies, and, when possible, from a combination of the two. They are not fixed values but are reviewed annually by the Committee on Threshold Limits for changes, revisions, or additions as further information becomes available. Threshold limits should be used as guides in the control of health hazards and should not be regarded as fine lines between safe and dangerous concentrations. They represent only conditions under which it is felt that workers may be repeatedly exposed, day after day, without adverse effect on their health. The figures listed refer to weighted average concentrations of an eight-hour working shift rather than a maximum which is not to be exceeded even momentarily. The amount by which these figures may be exceeded for short periods during the workday depends upon a number of factors, such as the nature of the contaminant, whether very high concentrations even for short periods produce acute poisoning, whether the results are cumulative, the frequency with which high values occur and for what periods of time. All must be taken into consideration in arriving at a decision as to whether a hazardous situation is deemed to exist.

These values are not intended for use, or for modification for use, in the evaluation or control of community air pollution or air-pollution nuisances.

The Committee welcomes the suggestion of substances to be added to the list and also comments, references, or reports of experience with these materials.

Recommended Values

GASES AND VAPORS

Substance	p.p.m.[a]	Approx. mg. per cu. m.[b]
Acetaldehyde	200	360
Acetic acid	10	25
Acetic anhydride	5	20
Acetone	1,000	2,400
Acrolein	0.5	1.2
Acrylonitrile	20	45
Allyl alcohol	5	12
*Allyl chloride	5	15
Allyl propyl disulfide	2	12
Ammonia	100	70
Amyl acetate	200	1,050
Amyl alcohol (isoamyl alcohol)	100	360
Aniline	5	19
Arsine	0.05	0.2

(*continued*)

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[20] Allan L. Coleman *et al., A.M.A. Arch. Ind. Health,* **16,** 261–65 (Sept., 1957).

GASES AND VAPORS *(continued)*

Substance	p.p.m.[a]	Approx. mg. per cu. m.[b]
Benzene (benzol)	25	80
Benzyl chloride	1	5
Bromine	1	7
Butadiene (1,3-butadiene)	1,000	2,200
Butanone (methyl ethyl ketone)	250	740
Butyl acetate (*n*-butyl acetate)	200	950
Butyl alcohol (*n*-butanol)	100	300
Butylamine	5	15
Butyl cellosolve (2-butoxyethanol)	50	240
Carbon dioxide	5,000	9,000
Carbon disulfide	20	60
Carbon monoxide	100	110
Carbon tetrachloride	25	160
Cellosolve (2-ethoxyethanol)	200	740
Cellosolve acetate (2-ethoxyethyl acetate)	100	540
Chlorine	1	3
Chlorine trifluoride	0.1	0.4
Chlorobenzene (monochlorobenzene)	75	350
Chloroform (trichloromethane)	100	490
1-Chloro-1-nitropropane	20	100
*Chloropicrin	1	7
Chloroprene (2-chloro-1,3-butadiene)	25	90
Cresol (all isomers)	5	22
Cyclohexane	400	1,400
Cyclohexanol	100	410
Cyclohexanone	100	400
Cyclohexene	400	1,350
Cyclopropane	400	690
*Decaborane	0.05	0.3
Diacetone alcohol (4-hydroxy-4-methyl-2-pentanone)	50	240
Diborane	0.1	0.1
o-Dichlorobenzene	50	300
Dichlorodifluoromethane	1,000	4,950
1,1-Dichloroethane	100	400
1,2-Dichloroethane (ethylene dichloride)	100	400
1,2-Dichloroethylene	200	790
Dichloroethyl ether	15	90
Dichloromonofluoromethane	1,000	4,200
1,1-Dichloro-1-nitroethane	10	60
Dichlorotetrafluoroethane	1,000	7,000
Diethylamine	25	75
Difluorodibromomethane	100	860
Diisobutyl ketone	50	290
Dimethylaniline (*N*-dimethylaniline)	5	25
Dimethylsulfate	1	5
Dioxane (diethylene dioxide)	100	360
Ethyl acetate	400	1,400
*Ethyl acrylate	25	100

GASES AND VAPORS *(continued)*

Substance	p.p.m.[a]	Approx. mg. per cu. m.[b]
Ethyl alcohol (ethanol)	1,000	1,900
Ethyl amine	25	45
Ethyl benzene	200	870
Ethyl bromide	200	890
Ethyl chloride	1,000	2,600
Ethyl ether	400	1,200
Ethyl formate	100	300
Ethyl silicate	100	850
Ethylene chlorohydrin	5	16
Ethylenediamine	10	30
Ethylene dibromide (1,2-dibromoethane)	25	190
Ethylene imine	5	9
Ethylene oxide	50	90
Fluorine	0.1	0.2
Fluorotrichloromethane	1,000	5,600
Formaldehyde	5	6
*Furfural	5	20
Gasoline	500	2,000
Heptane (*n*-heptane)	500	2,000
Hexane (*n*-hexane)	500	1,800
Hexanone (methyl butyl ketone)	100	410
Hexone (methyl isobutyl ketone)	100	410
Hydrazine	1	1.3
Hydrogen bromide	5	17
Hydrogen chloride	5	7
Hydrogen cyanide	10	11
Hydrogen fluoride	3	2
Hydrogen peroxide, 90%	1	1.4
Hydrogen selenide	0.05	0.2
Hydrogen sulfide	20	30
Iodine	0.1	1
Isophorone	25	140
Isopropylamine	5	12
Mesityl oxide	50	200
Methyl acetate	200	610
Methyl acetylene	1,000	1,650
*Methyl acrylate	10	35
Methyl alcohol (methanol)	200	260
Methyl bromide	20	80
Methyl cellosolve (2-methoxyethanol)	25	80
Methyl cellosolve acetate (ethylene glycol monomethyl ether acetate)	25	120
Methyl chloride	100	210
Methylal (dimethoxymethane)	1,000	3,100
Methyl chloroform (1,1,1-trichloroethane)	500	2,700
Methylcyclohexane	500	2,000
Methylcyclohexanol	100	470
Methylcyclohexanone	100	460
Methyl formate	100	250
Methyl isobutyl carbinol (methyl amyl alcohol)	25	100

(continued)

GASES AND VAPORS *(continued)*

Substance	p.p.m.[a]	Approx. mg. per cu. m.[b]
Methylene chloride (dichloromethane)	500	1,750
Naphtha (coal tar)	200	800
Naphtha (petroleum)	500	2,000
Nickel carbonyl	0.001	0.007
*Nitric acid	5	25
p-Nitroaniline	1	6
Nitrobenzene	1	5
Nitroethane	100	310
Nitrogen dioxide	5	9
Nitroglycerin	0.5	5
Nitromethane	100	250
2-Nitropropane	50	180
Nitrotoluene	5	30
Octane	500	2,350
Ozone	0.1	0.2
Pentane	1,000	2,950
Pentanone (methyl propyl ketone)	200	700
Perchlorethylene (tetrachloroethylene)	200	1,350
Phenol	5	19
Phenylhydrazine	5	22
Phosgene (carbonyl chloride)	1	4
Phosphine	0.05	0.07
Phosphorus trichloride	0.5	3
Propyl acetate	200	840
Propyl alcohol (isopropyl alcohol)	400	980
Propyl ether (isopropyl ether)	500	2,100
Propylene dichloride (1,2-dichloropropane)	75	350
Propylene imine	25	60
Pyridine	10	30
Quinone	0.1	0.4
Stibine	0.1	0.5
Stoddard solvent	500	2,900
Styrene monomer (phenylethylene)	100	420
Sulfur dioxide	5	13
Sulfur hexafluoride	1,000	6,000
Sulfur monochloride	1	6
Sulfur pentafluoride	0.025	0.25
p-Tertiarybutyltoluene	10	60
1,1,2,2-Tetrachloroethane	5	35
*Tetrahydrofuran	200	590
Tetranitromethane	1	8
Toluene (toluol)	200	750
o-Toluidine	5	22
Trichloroethylene	200	1,050
Trifluoromonobromomethane	1,000	6,100
Turpentine	100	560
Vinyl chloride (chloroethylene)	500	1,300
Xylene (xylol)	200	870

TOXIC DUSTS, FUMES, AND MISTS

Substance	mg. per cu. m.[c]
Aldrin (1,2,3,4,10,10-hexachloro-1,4,4a,5,8,8a-hexahydro-1,4,5,8-dimethanonaphthalene)	0.25
Ammate (ammonium sulfamate)	15
Antimony	0.5
* ANTU (alpha naphthyl thiourea)	0.3
Arsenic	0.5
Barium (soluble compounds)	0.5
Cadmium oxide fume	0.1
* Calcium arsenate	0.1
Chlordane (1,2,4,5,6,7,8,8-octachlor-3a,4,7,7a-tetrahydro-4,7-methanoindane)	2
* Chlorinated camphene, 60%	0.5
Chlorinated diphenyl oxide	0.5
Chlorodiphenyl (42% chlorine)	1
* Chlorodiphenyl (54% chlorine)	0.5
Chromic acid and chromates (as CrO_3)	0.1
Crag herbicide (sodium 2-[2,4-dichlorophenoxy]ethanol hydrogen sulfate)	15
Cyanide (as CN)	5
2,4-D (2,4-dichlorophenoxyacetic acid)	10
* DDT (2,2-bis[*p*-chlorophenyl]-1,1,1-trichloroethane)	1
Dieldrin (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-1,4,5,-8-dimethanonaphthalene)	0.25
* Dinitrobenzene	1
Dinitroluene	1.5
Dinitro-*o*-cresol	0.2
EPN (*O*-ethyl *O*-*p*-nitrophenyl thionobenzenephosphonate)	0.5
* Ferbam (ferric dimethyl dithiocarbamate)	15
Ferrovanadium dust	1
Fluoride	2.5
* HETP (hexaethyl tetraphosphate)	0.1
Hydroquinone	2
Iron oxide fume	15
Lead	0.2
* Lead arsenate	0.15
Lindane (hexachlorocyclohexane, gamma isomer)	0.5
Magnesium oxide fume	15
Malathion (*O,O*-dimethyl dithiophosphate of diethyl mercaptosuccinate)	15
Manganese	6
Mercury	0.1
Mercury (organic compounds)	0.01
Methoxychlor (2,2-di-*p*-methoxyphenyl-1,1,1-trichloroethane)	15
Molybdenum	
(soluble compounds)	5
(insoluble compounds)	15
* Nicotine	0.5
Parathion (*O,O*-diethyl *O*-*p*-nitrophenyl thiophosphate)	0.1
Pentachloronaphthalene	0.5
Pentachlorophenol	0.5
Phosphorus (yellow)	0.1
Phosphorus pentachloride	1

(*continued*)

TOXIC DUSTS, FUMES, AND MISTS (*continued*)

Substance	mg. per cu. m.[c]
Phosphorus pentasulfide	1
Picric acid	0.1
* Pyrethrum	2
* Rotenone	5
Selenium compounds (as Se)	0.1
Sodium hydroxide	2
* Sodium fluoroacetate (1080)	0.1
* Strychnine	0.15
Sulfuric acid	1
TEDP (tetraethyl dithionopyrophosphate)	0.2
TEPP (tetraethyl pyrophosphate)	0.05
Tellurium	0.1
Tetryl (2,4,6-trinitrophenylmethylnitramine)	1.5
* Thallium (soluble compounds)	0.1
* Thiram (tetramethyl thiuram disulfide)	5
Titanium dioxide	15
Trichloronaphthalene	5
Trinitrotoluene	1.5
Uranium	
(soluble compounds)	0.05
(insoluble compounds)	0.25
Vanadium	
(V_2O_5 dust)	0.5
(V_2O_5 fume)	0.1
* Warfarin (3-[α-acetonylbenzyl]-4-hydroxycoumarin)	0.5
Zinc oxide fumes	15
Zirconium compounds (as Zr)	5

Radioactivity: For permissible concentrations of radioisotopes in air, see *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water*, Handbook 52. U. S. Department of Commerce, National Bureau of Standards, March, 1953. In addition, see *Permissible Dose from External Sources of Ionizing Radiation*, Handbook 59, U. S. Department of Commerce, National Bureau of Standards, Sept. 24, 1954.

Revision of the two publications mentioned above is in progress.

MINERAL DUSTS

Substance	m.p.p.c.f.[d]
Aluminum oxide	50
Asbestos	5
Dust (nuisance, no free silica)	50
Mica (below 5% free silica)	20
Portland cement	50
Talc	20
Silica	
high (above 50% free SiO_2)	5
medium (5 to 50% free SiO_2)	20
low (below 5% free SiO_2)	50
Silicon carbide	50
Soapstone (below 5% free SiO_2)	20

TENTATIVE VALUES

Substance	p.p.m.[a]	Approx. mg. per cu. m.[b]
Acetylene tetrabromide	1	14
Allyl glycidyl ether (AGE)	10	45
Beryllium		$2\ \gamma/\text{m.}^3$
Boron trifluoride	1	3
n-Butyl glycidyl ether (BGE)	50	270
* Butyl mercaptan	10	35
Chloroacetaldehyde	1	3
* Chlorobromomethane ($Cl\ Br\ CH_2$)	400	2,100
Diglycidyl ether (DGE)	10	55
Dimethyl formamide	20	60
Dipropyleneglycolmethylether	100	600
* Ethyl mercaptan	250	640
* Furfuryl alcohol	50	200
Glycidol	50	150
Isopropyl glycidyl ether (IGE)	50	240
Lithium hydride		$25\ \gamma/\text{m.}^3$
* Methyl mercaptan	50	100
a-Methyl styrene	100	480
Monomethyl aniline	2	9
Paradichlorobenzene	75	450
* Perchloromethyl mercaptan	0.1	0.8
Phenyl glycidyl ether (PGE)	50	310
Propylene oxide	100	240
Tertiary butyl alcohol	100	300
* Tolylene-2,4-diisocyanate	0.1	0.7
Triethyl amine	25	100
Vinyl toluene	100	480
Yttrium and inorganic compounds		5
Xylidine	5	25
** Teflon decomposition products	0	0
** Pentaborane (B_5H_9)	0	0

* These values appeared on the tentative list for 1956.

** Until more data are forthcoming, it is important that atmospheric concentrations of these materials to which workers are exposed must be kept as near 0 as possible.

[a] Parts of vapor or gas per million parts of air by volume.

[b] Approximate milligrams per cubic meter of air.

[c] Milligrams of dust, fume, or mist per cubic meter of air.

[d] Millions of particles per cubic foot of air.

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Allan L. Coleman, *Chairman*

"The American Standards Association has for several years been attempting to establish standards for health and safety, and in 1936 it set up an advisory committee, which was reorganized in 1938 as a working committee to "determine, establish, and promulgate the allowable concentration limits of harmful gases, vapors, fumes, dusts, and mists." The relatively small number of standards for air contaminants that have been set by this body in the ensuing time is an indication of the magnitude of the task and suggests the necessity for a change in policy. This committee includes several recognized, competent authorities in the field of industrial toxicology, and also represents a good cross section of government and industry. There is much to be said in favor of such a body, but there are also pitfalls to be avoided. As long as the committee remains large, although it may be cumbersome, there is safety in numbers, and the large cross section of opinion may be relied upon to prevent the group from going too far astray. The most important precaution is that standards set by estimation, as nearly all of them necessarily must be, should not be considered, or portrayed, as ultimate levels of safety but only as tentative levels, representing the present consensus subject to reconsideration upon presentation of any properly weighted evidence. Another point that must be rigorously guarded against is the overbalancing of the committee in favor of persons whose training and qualifications are in the field of oratory instead of the field of industrial hygiene and toxicology. Neither the alarmists nor the purists who want to approach zero concentration of all harmful materials are sufficiently numerous, now, to seriously threaten to upset the proper balance. The opinions of all qualified and experienced people in the field should be sought. It should be remembered that the most thorough and complete toxicological data are useless unless accompanied by competent chemical analysis of the air, and the air samples must have been properly chosen to represent exposures existing during the period in which symptoms or manifestations of harmful effects developed, or were demonstrated to be absent.

CHAPTER VII

Sampling and Analysis of Atmospheric Contaminants

FRANK A. PATTY

In this chapter the problems involved in sampling and analyzing air contaminants are discussed from a general viewpoint with little regard for individual contaminants. It is not within the scope of this volume to give detailed methods of analysis. A rather complete compilation of such methods[1] has been published previously. In Volume II of this book outlines of, or reference to, methods of proved worth accompany the discussions of most contaminants. The methods so presented are in no sense to be interpreted as the only good methods, but rather methods that have been found suitable and reliable in practice. Volume III of this book covers methods of sampling and analysis in a more comprehensive manner.

Many analytical methods available to the industrial hygienist have been standardized and simplified until they require little thought or training. On the other hand, many seemingly simple tests require a fundamental understanding of solubility, the gas laws, partial pressures, and chemical reactions. In any industrial hygiene department many questions arise that can be answered only by a qualified chemist. The method of analysis to be used will depend upon the nature of the problem at hand rather than merely upon a "standard method." The trend is naturally toward methods that give prompt results with a degree of accuracy suited to the circumstances.

The first rule the industrial hygienist should adopt regarding analytical methods is never to rely upon a method until he has personally tried it out under controlled conditions, such as: *(1)* by sampling a synthetic atmosphere from a proportioning apparatus or from a gastight, impervious chamber of sufficient size to permit making and sampling mixtures without introducing significant errors; *(2)* by introducing a measured amount of contaminant into a device attached to the sampling arrangement in such a manner as to utilize the entire amount; or *(3)* by comparing with a device of proved worth by sampling from a common manifold at constant rate over the same period of time.

In evaluating concentrations of atmospheric contaminants of interest to the industrial hygienist, either extremely small quantities of materials must be determined or else provision must be made for sampling a large volume of air. The more toxic gases and vapors are of hygienic importance when found to be present in amounts even less than 1 ml. per cubic meter of air (1 p.p.m.), and many dusts and fumes are of interest in amounts of less than 1 mg. per cubic meter of air. Methods of analysis based upon microchemical technique, especially colorimetry, are frequently preferred because they can utilize a very small sample and thus involve less time and difficulties in sampling. Modes of expressing concentrations of atmospheric contaminants are discussed in Chapter VI (page 150).

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[1] M. B. Jacobs, *Analytical Chemistry of Industrial Poisons, Hazards, and Solvents.* 2nd ed., Interscience, New York-London, 1949.

GASES AND VAPORS

I. Methods Giving Quantitative Results in the Field

A. EVALUATING THE INTENSITY OF ODOR AND IRRITATION

Perhaps the most useful of all methods of detecting and estimating gases and vapors in the air is by their odors and irritant effects. Only a relatively few toxic ones are without either of these characteristics, notable among which is carbon monoxide. Many well-informed persons are inclined to scoff at the idea of considering odor and irritation as qualitative guides, much less quantitative ones, but that is either because they have never cultivated and educated the sense of smell or because for them that sense is physiologically substandard. The particular power of odors to quicken memory of associations has long been recognized. For instance, the odor of acetamide instantly calls up for most people the association of mice because it was first met as a constituent of mouse urine; the odor of nitrobenzene is associated with shoe polish because it once was widely used as an ingredient of shoe polish; and there are many others.

There have been various attempts to describe and classify the odor sensations. Henning,[2] in one of the best, recognizes six classes as follows: spicy, flowery, fruity, resinous (turpentine), foul and scorched. To further divide or add to these classes is a very difficult problem and, even though the memory of an odor may extend over many years, we seem to lack the proper descriptive adjectives. However, regardless of the quality of an odor, Gamble[3] has shown that in conformity with Weber's law the sense reaction to odors is proportional to the logarithm of the stimulus, that is, the intensity of sense reaction increases in arithmetical progression as the stimulus increases in geometrical progression. Katz and Allison[4] devised the odor and irritation scales shown in Tables 1 and 2, which with slight modification have since proved convenient for other investigators.

Odors are best determined by the first and second inhalations, as succeeding

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[2] Hans Henning, *Der Geruch*. Leipzig, 1924.

[3] Eleanor A. M. Gamble, *Am. J. Psychol.*, **10**, 82 (1898).

[4] S. H. Katz and V. C. Allison, *U. S. Bur. Mines Tech. Paper* No. **267**, 1920.

TABLE 1

Scale of Odor Intensities

Degree	Intensity	Description
0	No odor	No detectable odor
1	Very faint	Minimum, but positively perceptible odor
2	Faint	Weak odor, readily perceptible
3	Easily noticeable	Moderate intensity
4	Strong	Cogent, forcible odor
5	Very strong	Intense effect, may irritate

TABLE 2

Irritant Scale (Nasal Irritation and Eye Irritation)

Degree	Intensity	Description
0	No irritation	Not detectable
1	Faint	Just perceptible, not painful
2	Moderate	Moderate irritation, midway between 1 and 3
3	Strong	Discomforting, painful, but may be endured
4	Intolerable	Exceedingly painful, cannot be endured voluntarily

inhalations may tend to fatigue the sense of smell. Nasal irritation, throat irritation, and eye irritation, however, frequently increase with time, at least for the first several seconds and sometimes minutes. During the first attempts to evaluate odor and irritation, a subject may have considerable difficulty in making estimations that conform to the pattern of a representative group, but most persons overcome this difficulty rapidly so that with a group of six persons the deviation of individuals from the average is rarely more than one degree on the scale. As has been pointed out, however, some individuals are handicapped by having an impaired sense of smell; likewise, temporary impairment of anyone's sense of smell may result from various causes. Additional published data[5-8] on odor intensities are inadequate; therefore the problem more or less resolves itself into a matter of individual education, and industrial hygienists find it advantageous to note and record the quality and intensity of odors wherever an evaluated atmospheric contaminant is either encountered or prepared.

The graphs reproduced here are portrayals of data collected from experiments in synthetic atmospheres, where 4 to 7 investigators kept independent notes. Each point on the graph is an average of the individual results. Figure 1, prepared from data collected by the United States Bureau of Mines[6] showing the relation between odor intensity and concentrations of allyl mercaptan and ethyl mercaptan,

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[5] *International Critical Tables,* Vol. **1** (1926).

[6] S. H. Katz and E. J. Talbot, *U. S. Bur. Mines Tech. Paper* No. **480,** 1930.

[7] A. C. Fieldner, R. R. Sayers, W. P. Yant, S. H. Katz, J. B. Shohan, and R. D. Leitch. *U. S. Bur. Mines Monograph* No. **4,** 1931.

[8] F. A. Patty and W. P. Yant, *U. S. Bur. Mines Rept. Invest.* No. **2978,** 1929.

illustrates, on the part of allyl mercaptan, an irregularity or departure from Weber's law. Benzyl mercaptan, not shown, has a similar tendency except that the odor intensities below 3 appear to conform to a curve rather than to a straight line. The same is true of commercial heptane and hexane portrayed in Figure 2. Figure 3 portrays results with the same materials as in Figure 2 after they had been treated to remove traces of sulfur compounds. The heavy, solid, "intermittent exposure" lines represent the odor impression upon the first complete inhalation; the dotted lines represent the impression obtained by remaining in the atmosphere while the concentration was being built up over several minutes.

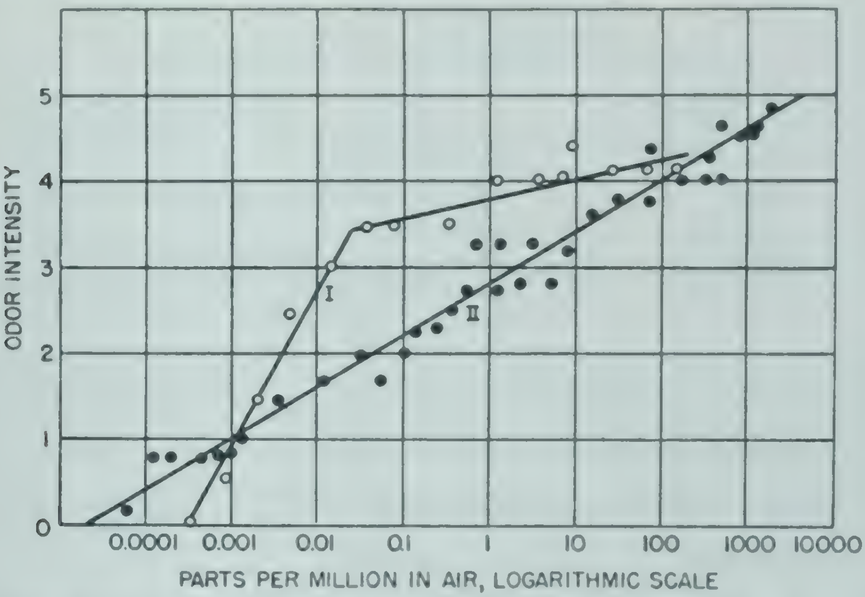

Figure 1. Odor intensity in relation to concentration of vapors of allyl mercaptan (I) and ethyl mercaptan (II).

Although the odor and irritation method of locating and evaluating exposures is very useful, its limitations are obvious: it offers no record, the sensitivity of the sense of smell varies with individuals, and the sense fatigues rapidly. Near the source of a toxic vapor the concentration in the air may be high, but it falls rapidly as the distance from the source increases. Thus an industrial hygienist, walking through a plant on a tour of investigation, may go through a low concentration with little or no warning odor, and by the time the area of moderately high concentration is reached fatigue may have occurred to an extent that would cause the vapor to be grossly underestimated or missed entirely. When the odor in a suspected area is being checked it may prove advantageous to enter it rapidly from uncontaminated air, holding the breath if necessary until the sampling zone is reached, then estimating the intensity of odor on the first inhalation. If the odors and irritant effects of atmospheres are used as guides, they can be so used to tremendous advantage, but they should never be proposed as accurate or acceptable means of analysis. A trained man, in estimating the concentration of an odorous or irritant

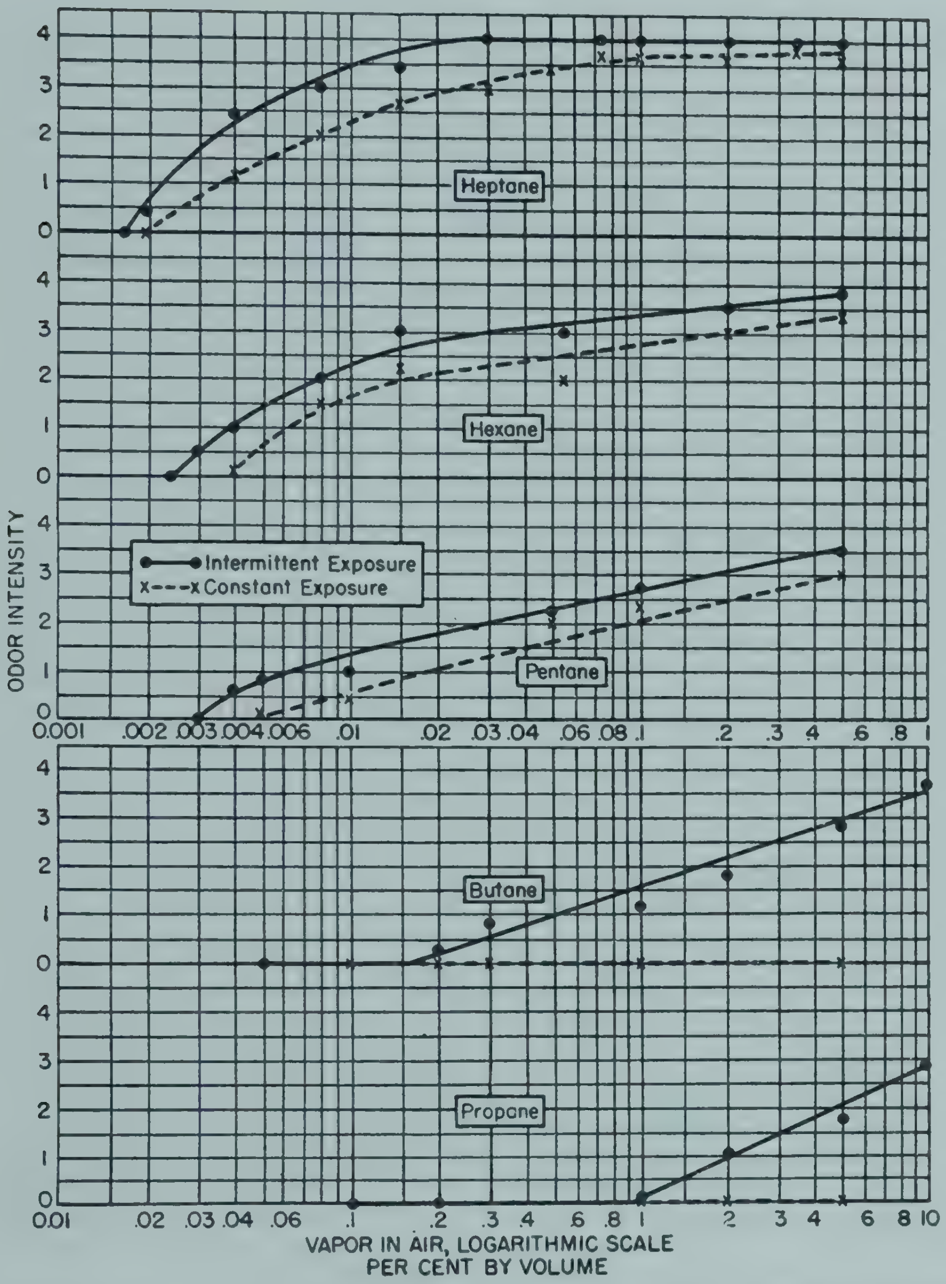

Figure 2. Relation between concentration of vapors of commercial paraffin hydrocarbons and odor intensity.

vapor or gas, is not likely to estimate less than $^1/_3$ nor more than 3 times the amount actually present; that is, if a trained investigator estimates by the odor a concentration of hydrogen cyanide to be 6 p.p.m., for instance, he can be reasonably certain the actual concentration is not below 2 p.p.m. nor above 18 p.p.m. This degree of accuracy is satisfactory in certain situations and entirely unsatisfactory in others.

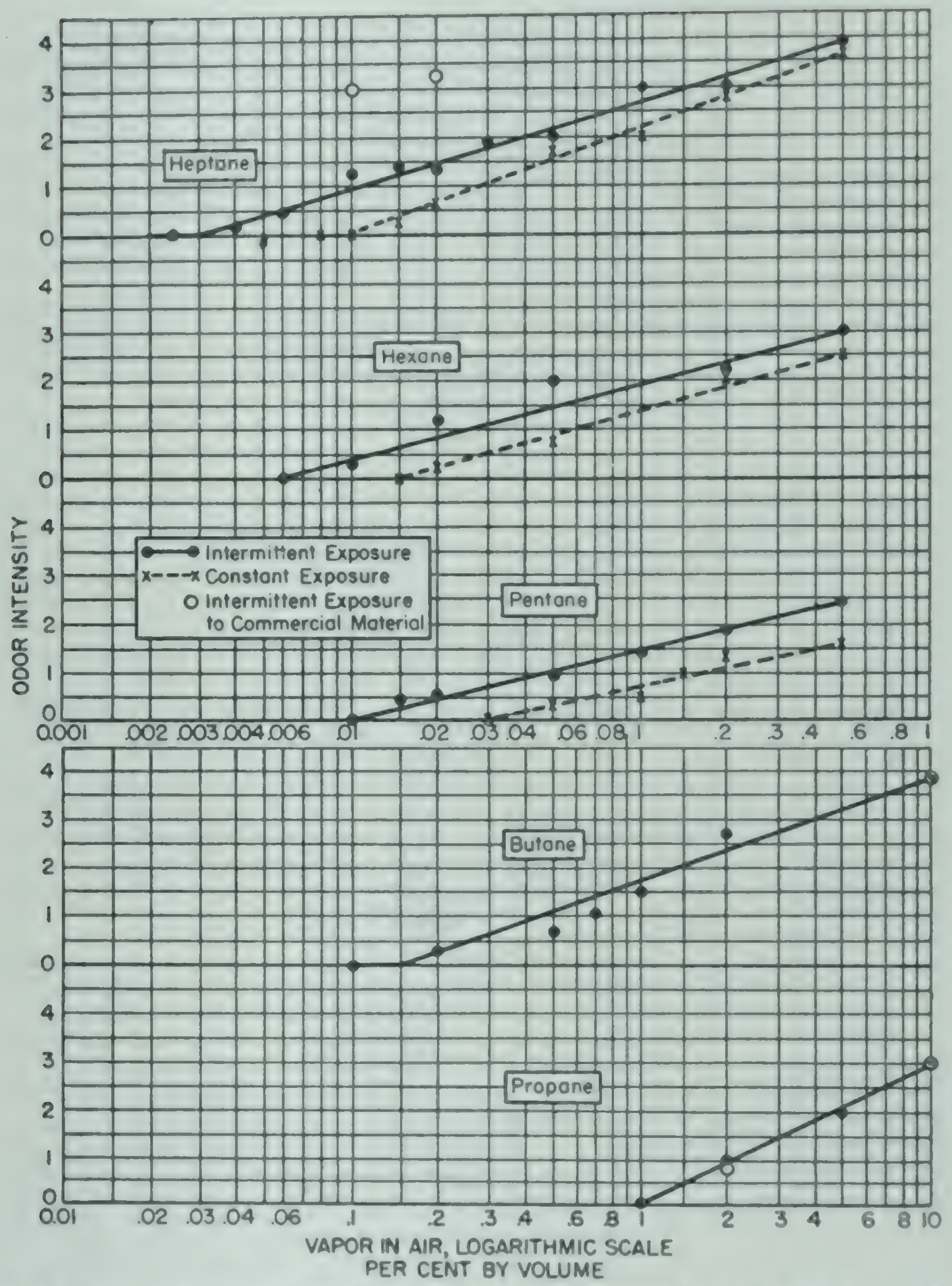

Figure 3. Relation between concentration of vapors of purified paraffin hydrocarbons and odor intensity.

B. PORTABLE RAPIDLY INDICATING DEVICES

Nearly all physical sampling methods are open to the same criticism: they are not specific, and it is sometimes impossible to tell whether the physical changes measured, especially small ones, are due to the presence of a particular gas or vapor or to some other cause; and in mixtures it is not always feasible to determine the percentage of each component. Nevertheless, the advantages of portability and immediate availability of results make some physical instruments immensely useful.

1. *Interferometer*

Perhaps the most dependable and most widely applicable physical instrument yet developed for field use is the 50-cm. portable gas interferometer. This instrument accurately measures minute changes in refractivity, so that it may successfully be used to determine low concentrations of contaminating gases or vapors in the atmosphere, providing the refractivity of the contaminant is sufficiently different from that of air, which is 291.7×10^{-6} at 0° C. and 760 mm. Hg pressure. Since refractivity is a function of density, as well as of molecular structure, slight changes in pressure and temperature have an important bearing on results and must be carefully controlled. The light source must be of constant wave length and is usually an incandescent filament. The interferometer is a sensitive form of refractometer which, instead of measuring refraction directly, compares the refractivity of one gas to that of another. In air analysis, the usual standard of comparison is dry air, from which all carbon dioxide has been removed. This standard atmosphere must be at the same temperature and pressure as the atmosphere to be examined. An interferometer may be calibrated against known mixtures of vapor in air, of the same order of concentration as atmospheric mixtures in which it is to be employed. Also, it many be calibrated for absolute refractivity changes, that is, refractivity factor, by increasing the pressure of dry air in one cell, referred to similar dry air at constant atmospheric pressure in the other.[9] Once this refractivity calibration has been accomplished, instrument scale readings may be translated to vapor percentages by employing any reliable data on the refractivity of vapors and gases. These data are perhaps most readily utilized when presented as unit refractivity change ($U\Delta R$), that is, the change in the refractivity of dry air at 25° C. and 760 mm. Hg pressure due to the admixture of 1 per cent gas or vapor. The data given in Table 3 were obtained by vaporizing weighed amounts of solvents in a galvanized metal chamber having a volume of 604 cu. ft.

The concentration of a known vapor may be determined as follows:

$$\text{Percentage vapor in air} = \frac{\text{interferometer reading} \times \text{refractivity factor (of instrument)}}{\text{unit refractivity change (of vapor)}}$$

For example, in measuring benzene vapor, suppose the interferometer scale reading is increased 62 divisions or 0.62 revolution of the indicator dial above its reading in "fresh" air and each revolution is equivalent to a change in refractivity of 2.91×10^{-6}, the percentage of benzene would equal:

$$\frac{0.62 \times 2.91 \times 10^{-6}}{14.4 \times 10^{-6}} = 0.125 \ (1250 \text{ p.p.m.})$$

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[9] J. D. Edwards, *U. S. Bur. Mines Tech. Paper* No. **131,** 1919; F. A. Patty, *J. Ind. Hyg. Toxicol.,* **21,** 469 (1939).

TABLE 3

Unit Refractivity Change ($U\Delta R$)

Solvent	$U\Delta R \times 10^6$	Solvent	$U\Delta R \times 10^6$
Methyl alcohol	2.5	Heptane	19.2
Ethyl alcohol	5.4	Octane	22.7
n-Propyl alcohol	8.6	Cymene	25.9
n-Butyl alcohol	11.6	Cyclohexane	15.1
Amyl alcohol	14.3	Cyclohexene	14.4
Methyl amyl alcohol	16.7	Cyclohexanol	15.4
Ethyl formate	8.7	Cyclohexanone	13.7
Ethyl acetate	11.6	Methyl cyclohexane	17.5
n-Butyl acetate	18.0	Methyl cyclohexanone	16.3
Amyl acetate	20.4	Benzene	14.4
Ethyl propionate	14.7	Toluene	17.5
Furfural	13.1	Xylene	20.4
Acetone	7.6	Ethylbenzene	20.1
Butanone	10.2	Pyridine	12.7
Pentanone	13.1	Chloroform	11.3
Hexanone	16.1	Carbon tetrachloride	14.6
Hexone	16.6	*s*-Dichloroethylene	10.8
Heptanone	19.0	Trichloroethylene	13.7
Octanone	21.9	Tetrachloroethylene	16.9
Mesityl oxide	16.3	Ethylene dichloride	11.1
Isophorone	19.2	Propylene dichloride	13.6
Ethyl ether	11.9	Dichloroethyl ether	16.9
Isopropyl ether	17.8	Chlorobenzene	17.5
n-Butyl ether	23.0	Ethyl bromide	9.5
Cellosolve	11.6	Ethylene bromide	14.3
Dioxane	11.3	Ethyl iodide	12.8
Pentane	13.4	Carbon disulfide	11.3
Hexane	16.6	Water	—0.28

The refractivity of a mixture of vapors is the sum of the refractivities of the components. Water vapor gives a negative reading and if it has not been removed from the atmosphere to be sampled, any difference between the humidity of the atmosphere in which the zero point was set and the atmosphere to be sampled must be measured and taken into account.

2. Portable Orsat

The portable Orsat[10] consists of a 100-ml. gas buret and four pipets: one containing sodium hydroxide, one alkaline pyrogallate, one acid cuprous chloride solution, and the fourth being a slow combustion pipet for burning combustible gases. The apparatus is suitable for the determination of carbon dioxide, oxygen, nitrogen, methane, and some other combustibles, including carbon monoxide in high concentration. Concentrations of carbon monoxide high enough to be detected with this device are, however, immediately dangerous to life. The limit of accuracy is 0.2 to 0.3 per cent. The chief application of this device is in the analysis of the atmosphere in mines.

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[10] W. P. Yant and L. B. Berger, *U. S. Bur. Mines Miners' Circ.* No. **34**, 1936.

3. Combustion Devices

Combustible Gas Indicators. Combustible gas indicators of numerous kinds are available. In the majority of these instruments the atmosphere to be tested is drawn across a platinum filament which is heated by a dry cell. This filament forms one arm of a Wheatstone bridge and is balanced before use against another heated filament in an inert atmosphere. Any combustible gas in the sample drawn across the hot filament is oxidized or burned catalytically, which burning results in an increased temperature of the filament and a consequent increase in resistance to the flow of electricity. The increase in resistance is proportional to the amount of flammable gases or vapors in the sample and is measured by a meter that has a scale calibrated for certain classes of vapors to give readings directly in percentage of the lower flammable limit. The sensitivity of these devices varies from the less sensitive, calibrated in fourths of the lower flammable limit, to the most sensitive type, calibrated to a few p.p.m. These instruments are very useful in locating sources of combustible gases or vapors and in evaluating fire and explosion hazards. One of the most sensitive type is termed a "benzene indicator." All of them should be checked periodically against known mixtures of the vapor to be analyzed.

Carbon Monoxide Indicators. Carbon monoxide is perhaps most satisfactorily measured by drawing the air to be analyzed, at a constant rate, through Hopcalite, in which sensitive thermocouples are located. The Hopcalite catalyzes the union of carbon monoxide with oxygen to form carbon dioxide, and the heat generated by this reaction is converted to electrical energy by the thermopile and registered by a recording potentiometer or a millivoltmeter.[11] The air to be analyzed must be dried by suitable means, and must be freed of interfering combustible gases by drawing it through an activated carbon filter. Hydrogen, methane, and nitrogen dioxide are not readily removed by this treatment and, if present, will yield high results.

Self-contained, portable instruments embodying the above principle are available.[12] These portable instruments are sometimes subject to significant errors caused by variations in humidity and temperature, especially where measurements below 100 p.p.m. are desired. The difficulty of establishing constant zero readings can be lessened by recirculating the air through the instrument. This is especially helpful in cold weather when the air to be measured is warm and the reference air would be cold, or when the reference air is suspected of containing traces of carbon monoxide. Since this instrument is also subject to altitude fluctuations, it is unsuited to measuring low but significant amounts of carbon monoxide in airplanes.

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[11] S. H. Katz, D. A. Reynolds, H. W. Frevert, and J. J. Bloomfield, *U. S. Bur. Mines Tech. Paper* No. **355,** 1926.

[12] Carbon Monoxide Indicator, Mine Safety Appliances Co., Pittsburgh, Pa.

A special type of carbon monoxide indicator[13] for this latter purpose, said to be sensitive to 10 p.p.m. and not affected by altitude and temperature changes, has been developed for sale.

In all types the Hopcalite is subject to deterioration with use and it, as well as the filter for removing organic vapors and water vapor, must be renewed periodically. These instruments are valuable and dependable when properly maintained, but are completely unreliable unless they are serviced by competent men. It is good practice to calibrate them with a known mixture of carbon monoxide and air either periodically or else before each series of tests. Carbon monoxide–air mixtures may be purchased in cylinders; or the air mixtures may be made as required by metering carbon monoxide and air, each through a venturi-type flowmeter, into a mixing chamber. Carbon monoxide, with a purity of 98 per cent or better, is readily made by dropping formic acid into heated sulfuric acid and passing the gas through soda lime to remove acid vapors. The carbon monoxide thus generated or carbon monoxide purchased in cylinders may be used to make the desired mixtures.

Flame Safety Lamps. Flame safety lamps that have been approved by the United States Bureau of Mines[14] are satisfactory for the recognition and rough estimation of some combustible gases as well as of atmospheres deficient in oxygen.[15] Obviously they must be used correctly in flammable atmospheres in order to avoid accidental ignition of the atmosphere.[16]

4. Ultraviolet Absorption Devices

Ultraviolet absorption has been used successfully to measure mercury vapor,[17] and more or less successfully for trichloroethylene and some other vapors.[18] If this type of instrument can be developed with variable wave length and sensitivity control, it should prove useful for both qualitative and quantitative air analysis for gases and vapors, and especially so in mixtures of unknown composition. In the device for measuring trichloroethylene, light of a fixed wave length in the ultraviolet range is passed through an absorption cell onto a cell sensitive to ultraviolet light. When air containing vapors having an opacity to light of this wave length is passed through the cell, the depletion of transmission is proportional to the concentration of the vapor, providing the atmosphere is free of dust.

The following is a promising variation, involving analysis in the laboratory. Samples of some solvent vapors, collected by drawing the atmosphere through an especially good grade of granulated silica gel at about 1 liter per minute can be transported to the laboratory in glass-stoppered bottles, leached out with a small amount of methanol and an aliquot evaluated successfully by means of the Beckman ultraviolet spectrophotometer.[19]

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[13] W. P. Yant, personal communication.

[14] J. W. Paul, L. C. Ilsley, and E. J. Gleim, *U. S. Bur. Mines Bull.* No. **227**, 1924

[15] A. B. Hooker, E. J. Coggeshall, and G. W. Jones, *U. S. Bur. Mines Rept. Invest.*, No. **3327**, 1937.

[16] W. H. Tomlinson, *U. S. Bur. Mines Circ.* No. **7271**, 1944.

[17] T. T. Woodson, *Rev. Sci. Instr.*, **10**, 308 (1939).

[18] V. F. Hanson, *Ind. Eng. Chem., Anal. Ed.*, **13**, 119 (1941).

C. COLLECTION IN INDICATOR MEDIUM

Certain contaminants may be collected in scrubbers or impingers containing a liquid medium that by change of color serves as an indicator. By this means a predetermined amount of an atmospheric contaminant may be recognized; it is then only necessary to consider the volume of air that has been sampled up to the time of color change in order to estimate the concentration of the material. The accuracy of such methods is usually within the range of 80 to 98 per cent, depending upon the gas sampled and the efficiency of the scrubber. Although not entirely satisfactory for research work, or for the setting of standards of maximum permissible contamination, these methods are particularly useful in informing the industrial hygienist—in the field—of the order of intensity of contamination and therefore whether control is necessary, and if so, to what extent.

As an example of how this may be used to advantage, without adding an impractical burden of weight to the field equipment, consider the determination of ammonia or acid gases using the midget impinger, with or without special scrubbers, as the sampling device. The sampling rate must be accurately calibrated. The impinging liquid is water with a measured amount of standard 0.01 *N* acid or alkali containing 0.01 per cent methyl red indicator. The standard reagents can be carried in small glass-stoppered bottles and pipetted into the scrubbers as required. The skill of a chemist is required for making up the standard solutions, but any experienced industrial hygiene engineer, exercising ordinary care, can carry out the sampling technique of loading scrubbers in an uncontaminated atmosphere and noting the operating time required to produce a color change in the collecting liquid. The computation for a sampling rate of 2832 ml. per minute is: 1 ml. 0.01 *N* reagent = 0.2445 ml. monovalent gas at 25° C. and 760 mm. Hg pressure,

$$\frac{0.2445 \times 1{,}000{,}000 \times \text{ml. reagent}}{2832 \times \text{minutes}} = \frac{86 \times \text{ml.}}{\text{minutes}} =$$

p.p.m. for gases of one hydrogen equivalent

For gases having two hydrogen equivalents the formula becomes (43 × ml.)/minutes. This has been used successfully for ammonia and most of the common acid gases.

Hydrogen sulfide, sulfur dioxide, and hydrogen cyanide may be determined in a similar manner, employing 0.01 *N* iodine solution and starch indicator. The hydrogen cyanide is collected in a sodium bicarbonate solution containing the iodine. This reaction requires one mole of iodine for one of hydrogen cyanide, since each half of the molecule combines with an iodine atom:

$$\mathrm{NaCN} + \mathrm{I_2} \rightarrow \mathrm{NaI} + \mathrm{CNI}$$

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[19] E. M. Adams, personal communication.

Sulfur dioxide and hydrogen sulfide each require only the usual solution of iodine in potassium iodide, and the reactions are the common oxidation ones:

$$SO_2 + 2\ H_2O + I_2 \rightarrow H_2SO_4 + 2\ HI$$
$$H_2S + I_2 \rightarrow 2\ HI + S$$

A similar result is achieved by utilizing the color developed by the solution of the contaminant in the sampling medium. This simple type may be utilized in estimating ammonium picrate. Ammonium picrate in water, with no added reagents, produces sufficient color that 0.01 mg. in 10 ml. of water is readily distinguishable from none and from 0.02 mg. Each sample is collected until a visible color is obtained and then that color is compared with standards, in the field. (Ammonium picrate, TNT, Tetryl, and other contaminants in their class have been successfully collected by means of the midget impinger regardless of whether they occurred as vapor or particulate matter.) TNT and Tetryl samples may be collected and semiquantitative results may be obtained in the field by the use of diethylaminoethanol[20] in the impinger; but, because color develops gradually and continuously over many hours, really satisfactory results must await transportation to the laboratory. However, the use of permanent standards, and possibly an accelerator, would improve the results obtainable at the time of sampling. In its present stage of development the method is satisfactory only in the laboratory, where results may be determined with a spectrophotometer and compared with results obtained with standard solutions, due regard being taken of the time factor.

D. HAND PISTON PUMP, LUER SYRINGE, AND RUBBER-BULB COLLECTION DEVICES

Hand piston pumps and rubber aspirating bulbs have been used for collecting samples. These methods, which aim to avoid the more cumbersome, orthodox methods of sampling, may involve pulling the atmosphere through indicating granules, such as in the MSA hydrogen sulfide detector, the aromatic hydrocarbon detector, and the NBS carbon monoxide indicating tube.[21] Indicator paper or a scrubber may also be used. The pump may be calibrated and the sample measured by the number of piston strokes. Luer syringes have been used for measuring atmospheric samples and as reaction chambers for the determination of oxygen,[22] and also as a comparison chamber in the determination of nitrogen dioxide.[23] All examples of this class of sampling have as their purpose the keeping of sampling equipment to a minimum and also the obtaining of direct results in the field. Accuracy in some instances may, and in others may not, equal that obtained by longer and more cumbersome methods.

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[20] F. H. Goldman and D. E. Rushing, *J. Ind. Hyg. Toxicol.*, **25**, 164, 195 (1943).

[21] M. Shepherd, *A Preliminary Report of the N.B.S. Colorimetric Indicating Gel for the Rapid Determination of Small Amounts of Carbon Monoxide*, Natl. Bur. Standards, June 29, 1946.

[22] Y. Henderson and L. A. Greenberg, *J. Am. Med. Assoc.*, **96**, 1474 (1931).

[23] F. A. Patty and G. M. Petty, *J. Ind. Hyg. Toxicol.*, **25**, 361 (1943).

II. Methods Requiring Laboratory Analysis

A. HALOGENATED HYDROCARBONS COMBUSTION APPARATUS

Several devices have been proposed for the combustion of halogenated hydrocarbon vapors in the atmosphere. Passing the atmosphere through a heated tube containing a platinum foil was first utilized by Pregl[24] and several modifications for field use have been made.[25] The use of a free flame for the combustion analysis of this class of vapors was introduced by Patty, Schrenk, and Yant.[26] A similar plan was followed by Winter,[27] using a lamp method. A sulfur lamp apparatus was used by Wirth and Stross[28] to determine sulfur and chlorine in gasoline, and since then has been used for the determination of various organic chlorides in flammable liquids. Elkins[29] scrubbed carbon tetrachloride from the air with amyl acetate and burned it in a modified sulfur lamp. In all of these methods combustion was found to be quantitative. The percentage absorption of the products of combustion varies with the type of apparatus employed and may be seriously low when sampling concentrations on the order of 0.2 per cent or higher, and when using a small volume of absorbing liquid. In the combustion-tube method at least $^1/_2$ hour is required to collect the sample, after which the combustion products must be washed into a suitable flask and taken to the laboratory for titration, which is simple and rapid. The sulfur-lamp method requires more time since it involves scrubbing the vapor from the air before it can be burned in the lamps. The combustion methods are specific only for the class of halogenated vapors and gases (chlorides, bromides, or iodides), and organic halogens cannot be differentiated from acid halogens, unless sampled through a filter to remove acid halogens. Methods employing glass apparatus are not applicable to the determination of fluorides, because the fluoride combustion products attack glass. These combustion methods obviously give an integrated result for the entire period of sampling.

It will be of interest to compare sets of figures obtained independently by two experienced operators, one with the Willson combustion apparatus for halogenated hydrocarbons, and one with the Zeiss gas interferometer. The samples were taken over a 30-minute period in a room of a plant where carbon tetrachloride was being splashed from bottles onto a table top. The samples were drawn through a 3-foot glass tube extension on the combustion tube of the Willson apparatus, the extension being provided with a side connection or Y leading to the interferometer. The result obtained with the Willson apparatus was 101.6 p.p.m. carbon tetrachloride. The results obtained with the interferometer, plotted in Figure 4, average 123 p.p.m., with a minimum of 6 p.p.m. and a maximum of 1096 p.p.m. during the $^1/_2$-hour sampling period.

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[24] F. Pregl, *Quantitative Organic Microanalysis.* Trans. by Tylemann. 2nd ed., Blakiston, Philadelphia, 1924.

[25] W. M. Malisoff, *Ind. Eng. Chem., Anal. Ed.,* **7,** 428 (1935); B. D. Tebbens, *J. Ind. Hyg. Toxicol.,* **19,** 204 (1937); A. N. Setterlind, *Determination of Chlorinated Hydrocarbons (Except Chloronaphthalenes).* Illinois State Dept. of Health, Div. of Industrial Hygiene, Chicago, Ill.; H. C. Dudley, *U. S. Public Health Repts.,* **56,** 102 (1941).

[26] F. A. Patty, H. H. Schrenk and W. P. Yant, *Ind. Eng. Chem., Anal. Ed.,* **4,** 259 (1932).

[27] P. K. Winter, *Ind. Eng. Chem., Anal. Ed.,* **15,** 571 (1943).

[28] C. Wirth and M. J. Stross, *Ind. Eng. Chem., Anal. Ed.,* **5,** 85 (1933).

[29] H. B. Elkins, A. K. Hobby, and J. E. Fuller, *J. Ind. Hyg. Toxicol.,* **19,** 474 (1937).

More than one interpretation of this variation in results is possible. It may be that we have here a true measure of the actual difference between the mean of this series of grab samples and the average obtained from an integrated continuous sample.

At first glance one might say that the difference here of 21 p.p.m. between the two methods is within the experimental error of the interferometer and assume the combustion result to be correct. However, although there is a probable error of 20 p.p.m. for one reading on the interferometer, for a series of readings the result obtained is much closer to the correct one, and probabilities are that the combustion apparatus gave slightly low results,[30] especially for the period of time that the concentration was above 500 p.p.m. The correct result may well be assumed to have been 5 to 15 per cent above the combustion results, or between 107 and 117 p.p.m.

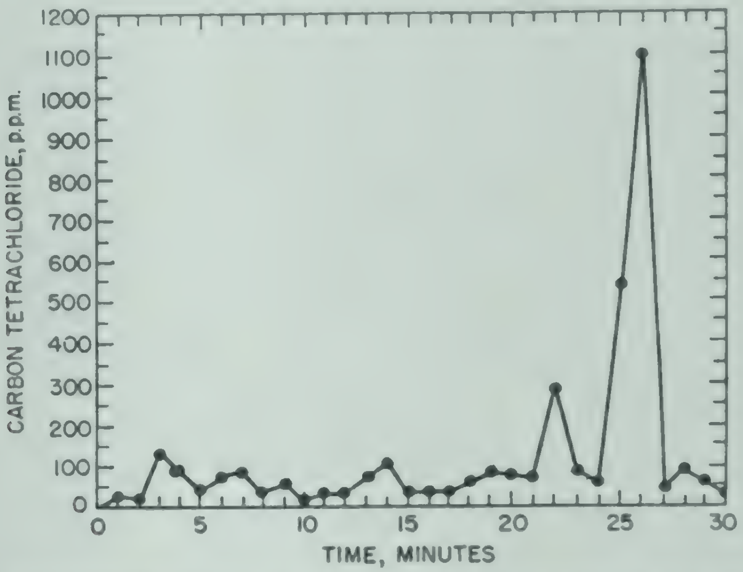

Figure 4. Carbon tetrachloride vapor in air as determined by means of a gas interferometer.

The graph is an interesting illustration of another point, that is, of the futility of trying to evaluate a variable exposure by a single, or even a few, random grab samples. To be reliable the grab samples must be taken at frequent regularly spaced intervals. These particular samples represent an abnormal variation in concentration in that the spillage was frequent and variable, with constantly good general ventilation. Under such conditions, if the chief concern is maximum level of contamination, the industrial hygienist will choose properly spaced grab samples; if toxicity is more dependent upon cumulative exposures, he may prefer the integrated sample.

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[30] F. H. Goldman and C. G. Seegmiller, *J. Ind. Hyg. Toxicol.*, **25**, 181 (1943).

B. ADSORPTION FOR EVALUATION BY WEIGHT

Many variations of the adsorption method introduced by Greenburg[31] have been proposed by different investigators. The principle is the same in all and the shortcomings are similar. The usual adsorbent is activated charcoal or silica gel confined in convenient weighing tubes. These materials are not selective but readily adsorb most vapors and gases, especially those of high molecular weight. The sample of vapor in air is drawn through the adsorbent at a constant rate, usually 1 liter or less per minute, and after a suitable sample is collected the tube with its contents is weighed. Since practice has shown that variations in weight of silica gel tubes, and even more so of charcoal tubes, often amount to more than 5 mg. within a 24-hour period as a result of static charges, moisture, and other factors, even though no air has been passed through them, it is obvious that dependable results require samples weighing at least 50 mg. If the sample is collected at the rate of 1 liter per minute, and it is desired to determine the concentration of benzene in the air of a room where the average concentration amounts to 50 p.p.m. (0.16 mg. per liter), it is evident that a sampling time of about 5 hours would be required for dependable results. For higher concentrations this method is more applicable, since less time is required to obtain a sample of suitable weight. Tubes equilibrated for several hours in air of the same humidity and temperature as the atmosphere to be analyzed may be used without filters for removing water vapor and carbon dioxide from the air sampled. However, it is the usual practice in the interest of accuracy to employ such filters wherever they do not alter the concentration of the contaminant. Moskowitz and Burke[32] found it advantageous to have filters before and after the adsorbent. The ones ahead of the adsorbent removed water and carbon dioxide from the air, and the ones following the adsorbent collected water and carbon dioxide lost by the adsorbent as the air passed over it. The adsorption method obviously collects an integrated sample, while it is frequently desirable to follow the changes in concentration in order to obtain information on the height and duration of peak values. The method is applicable to gases and vapors of high molecular weight and moderate toxicity. It must always be borne in mind that many vapors cannot be filtered through drying agents and soda lime without partial or even complete loss within those agents. Since the method warrants an accuracy only to the nearest milligram, weighing usually can be accomplished at any laboratory or in the field. Vapor samples adsorbed on activated carbon or silica gel may also be transported to the laboratory, released by passing heated air through the adsorbent, and the vapor determined by suitable chemical methods of analysis (see also pages 185 and 186).

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[31] L. Greenburg, *U. S. Pub. Health Repts.*, **41**, 1516 (1926); W. A. Cook and A. L. Coleman, *J. Ind. Hyg. Toxicol.*, **18**, 194 (1936).

[32] S. Moskowitz and W. J. Burke, *N. Y. State Ind. Bull.*, **17**, 168 (1938).

C. CONDENSATION AT LOW TEMPERATURES

Most vapors may be collected successfully by drawing them through a suitable chamber immersed in a low-temperature bath, the temperature required being that at which the vapor pressure of the liquid or solid to be collected approaches zero. A metering device for the air mixture is necessary, and the rate must be slow enough to permit condensation and avoid loss of mist or dust of the condensed material. The design of the condensation chamber must be such as to avoid choking with either ice or solid contaminant condensed from the air sampled. The condensed material may be weighed, measured by volume, or determined by quantitative chemical analysis. Ice, solid carbon dioxide, and liquid air have each been employed as the refrigerating medium.

D. COLLECTION BY ABSORPTION OR ADSORPTION FOR LABORATORY ANALYSIS

The collecting device here may be any of several types of scrubbers or impingers, and the collecting medium may be granulated silica gel or a liquid of low volatility, either of which must be a tenacious adsorbent or absorbent for the contaminant or else it must fix the contaminant by chemical combination. The collectors may be used singly or in series depending upon their established efficiency. The collected samples are transported to the laboratory and evaluated by various means, which include colorimetric, volumetric, polarographic, or spectrographic analyses, the use of the ultraviolet or infrared spectrometer, and combustion (see also pages 182 and 189).

E. SAMPLING IN EVACUATED BOTTLES

1. Vacuum Bottle Samples

Samples are conveniently collected in vacuum bottles for the determination of oxygen, carbon dioxide, and combustible gases in the analysis of mine gases by means of the Haldane[33] or Orsat[10] gas burets; for the determination of radon by means of especially constructed electrometers (page 731); for the determination of nitrogen oxides by the phenoldisulfonic acid method; and for many other determinations. Usually this type of sample is not larger than 1 liter. The sample is readily taken upon opening the bottle to the atmosphere, either by opening a glass stopcock or a pinchcock on a short length of heavy-walled tubing, or by breaking off the tip of a sealed inlet orifice, being careful not to warm the bottle by contact with the hands, and then closing or sealing the orifice.

2. Samples in Partially Evacuated Bottles

Samples may be conveniently taken in partially evacuated bottles of any size up to 20 liters. A measured volume of a suitable absorbent liquid is added to a calibrated bottle and the bottle is partially evacuated by a hand pump or other means, the residual partial pressure being recorded. The bottle is opened in the atmosphere to be sampled. It should then be taken to the laboratory, or to an uncontaminated zone, shaken well, and the contents washed into a suitable container with 2 or 3 successive portions of wash solution. After this, analysis may be made by appropriate methods.

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[33] L. B. Berger and H. H. Schrenk, *U. S. Bur. Mines Circ.* No. **7017,** 1938.

The volume of the sample is computed as follows:

$$V_s = (V - A)\frac{P_2 - P_1}{P_2}$$

where V_s = sample volume, V = volume of bottle, A = volume of absorbent added to the bottle, P_1 = residual partial pressure in the bottle, and P_2 = atmospheric pressure at the time and place of sampling.

F. SPECTROMETRY

1. *Infrared*

The infrared spectrometer[34] is a relatively new tool with great possibilities for use in industrial hygiene as a means of recognizing and evaluating organic materials in the air. The basis of application is that practically all organic substances possess selective absorption at certain frequencies in the infrared portion of the spectrum. The essential parts of the apparatus are a heat source emitting a continuous range of the wave lengths desired; a means of dispersing the radiation and providing narrow wave length bands at accurately known wave length positions (for this purpose prisms of sodium chloride, potassium bromide, and so forth, are supplied); cells for placing a suitable thickness of material for analysis in the path of the radiation; and a detector, such as a sensitive thermocouple and amplifier, for accurately measuring the radiation. Absorption cells of various lengths have been used, from 0.05 mm. for liquids and solids to several meters for gases. The size, weight, and complexity of the apparatus do not make it attractive as a portable instrument; and the length of absorption path must be many meters in order to make the instrument suitable for measuring a few p.p.m. of most gases and vapors in air. However, when the material to be analyzed is absorbed or dissolved in a liquid, analysis is readily accomplished, providing a liquid vehicle has been chosen that has no interfering absorption bands in the significant range for the material to be analyzed. The absorption pattern furnishes positive identification of single compounds having a known pattern; furnishes helpful clues to the composition of complex mixtures (superimposed patterns); and identifies linkages, bonds, and groups in obscure compounds. It is a quantitative tool as well, since Beer's law has been found true for this region of the spectrum (the absorption is proportional to the concentration of absorbent in the solution). Many ranges of wave lengths in the spectrum, between visible and ultra short radio waves, have yet to be explored, largely because of the difficulty of generating, controlling, dispersing, and measuring the intensity of these waves.

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[34] R. B. Barnes, U. Liddel, and V. Z. Williams, *Ind. Eng. Chem., Anal. Ed.*, **15**, 659 (1943).

2. Ultraviolet

Several organic solvents, especially in the aromatic series, have characteristic absorption patterns in the ultraviolet region of the spectrum.[35] The patterns can be used to identify very small amounts of solvents, while the opacity of the solvent at specific wave lengths can be used to measure the amounts. As in the case of infrared analysis, a sample must be collected from the air by condensations, by collection on silica gel (page 182), or by scrubbing air through a tenacious nonvolatile solvent that has no interfering absorption pattern. It is frequently necessary to refrigerate the scrubber in order to obtain high collection efficiency.

3. Light Absorption

Visible light spectrometry[36] is similar to infrared and ultraviolet spectrometry except that there are fewer compounds having distinctive absorption patterns. In spectrometry accurate results require a source of radiant energy confined to a narrow band of known (calibrated and checked) wave length, recognition and consideration of interfering absorption, and reliable measurement of transmitted energy.

G. THERMAL CONDUCTIVITY

The thermal conductivity of gases and vapors can be used to measure or monitor vapor-air mixtures. Commercial instrumentation to fractionate vapors and measure their thermal conductivity is now available. Gas chromatography, a technique combining fractionation and thermal conductivity, requires quantities of only a few milligrams for identification and measurement of paint and lacquer thinners and other volatile solvents of interest to industrial hygienists.

DUSTS, FUMES, AND SMOKES

I. Sampling

The instrument to be employed for sampling and evaluating particulate matter in the atmosphere will depend upon the availability of instruments, place to be sampled, nature of the contaminant, and purpose of the investigation.

A. IMPINGEMENT

There are several dust-sampling instruments that employ the principle of impingement. Dust carried by air at high velocity is impinged against a plate, where it is arrested by an agent, such as a film of water or other liquid, gelatin, or grease.

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[35] M. E. Maclean, P. J. Jencks, and S. F. Acree, *J. Research Nat'l Bur. Standards*, **34**, 271 (1945).

[36] M. G. Mellon, *Ind. Eng. Chem., Anal. Ed.*, **17**, 81 (1945).

1. Greenburg-Smith Apparatus

In the United States the Greenburg-Smith[37] standard impinger and its midget counterpart are the most widely used instruments for obtaining dust samples for evaluation by counting. In the standard instrument air is drawn through an impinger nozzle or orifice 2.3 mm. in diameter at the rate of 1 cu. ft. per minute and impinged against a glass plate set perpendicular to, and 5 mm. distant from, the orifice. Each orifice must be calibrated and, if necessary, adjusted to this size and flow. The plate may be the bottom of the sample flask itself. The plate is covered to a depth of at least 1 inch with dust-free water or other suitable liquid, which serves to trap and retain the dust particles after they strike the plate. The device is usually equipped with an electrically driven air pump, but may be obtained for hand operation, or with an ejector utilizing compressed air as the means of aspiration.

This device is suitable for sampling all air-borne dusts greater than 0.7 μ in diameter (dust within the range of definition by light-field technique), but at the standard rate of flow its efficiency for dusts of smaller size falls off rapidly. When set up with two impinger flasks in series, however, it can be used for particles somewhat smaller in size, such as lead fumes and fluoride fumes, the greater part of which are below 0.5 μ in diameter. Frequently the greater portion of freshly formed fumes is caught in the second impinger flask, perhaps because the particles have become moistened in passing through the first flask and so are more easily trapped in the second. Another possible explanation is that condensation of water upon the individual particles takes place as a result of the cooling of the saturated air as it suddenly expands upon emerging from the orifice into the second flask.

With freshly generated lead fume,[38] the efficiency has been found to range from 55 to 60 per cent, 34 to 37 per cent in the second flask, while with fumes 1 to 3 hours after generation 60 to 65 per cent was collected in the first impinger and 13 to 32 per cent in the second, for a total collection efficiency of 78 to 92 per cent. With fluoride fume collected in a magnesium foundry the second impinger contained 13 to 38 per cent of the total collected (see page 193), and the collection efficiency compared with a commercial electrostatic precipitator was 94 to 120 per cent. A small and undetermined portion of the fluoride contamination was doubtless gaseous.

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[37] L. Greenburg and G. W. Smith, *U. S. Bur. Mines Rept. Invest.*, No. **2392,** 1922; C. E. Brown and H. H. Schrenk, *U. S. Bur. Mines Circ.* No. **7026,** 1938.

[38] J. B. Littlefield, Florence Feicht, and H. H. Schrenk, *U. S. Bur. Mines Rept. Invest.*, No. **3401,** 1938.

2. The Midget Impinger

The midget impinger is similar to the standard instrument except that it is usually hand-operated and draws a sample volume of 2.8 liters per minute through an orifice 1 mm. in diameter. Each impinger nozzle must be calibrated, as deviations in nozzle size of over 50 per cent are found. This instrument has been shown to be as satisfactory as the standard apparatus for sampling most dusts in the range of 0.7 to 10 μ, but it is not suited to the sampling of particles below 0.5 μ, such as fumes. Its suitability for sampling asbestos fibers has been questioned. It can be operated by a hand crank and is therefore independent of a power supply, and is suitable for use in flammable vapors or dusts. The entire impinger, complete with 9 flasks, is contained in a relatively light and easily portable case.

3. The Konimeter

The konimeter is a dust-sampling instrument introduced by R. M. Kotze in 1916, and later modified. In its present form (Zeiss Konimeter) it consists essentially of a small valveless spring-operated piston pump and a circular plate for impingement of the dust. When the piston is depressed it is held against the compression of the operating spring by a catch. Releasing the catch allows the piston to move rapidly to a stop and creates at the discretion of the operator a 2.5-ml. or a 5-ml. void, pulling atmospheric air through a round 0.5- to 0.6-mm. orifice and impinging it against a circular glass plate held 0.5 to 0.6 mm. distant from and perpendicular to the impinging orifice. The circular plate, held in a metal rim, is covered with an adhesive film to retain the dust particles, and has 30 numbered, equally spaced sample positions.

For use, the glass disk is cleaned, coated with an adhesive (glycerine jelly is recommended by the United States Bureau of Mines[39]), examined under a microscope, and, if satisfactory, inserted in the konimeter or a spare carrying case. Usually several samples are taken in the same work area in order to estimate average conditions. The instrument is not satisfactory for high dust concentrations: even a 2.5-ml. sample of visibly dusty air is likely to be too much to count. For very low dust concentrations more than one 5-ml. sample may be taken at the same position of the disk. In the technique used by the United States Bureau of Mines, the samples are estimated by counting sectors of the spots under a microscope with 200 magnification, using light-field illumination. The counts cannot be directly compared to impinger counts, but are useful in estimating the effectiveness of dust-control methods, and for comparing dustiness in a situation where the type of dust remains more or less constant but its concentration varies with numerous conditions. The dust is counted without prior treatment. Ease and speed of sampling and counting are the chief advantages of the method. Techniques used in countries other than the United States vary from that described, but will not be elaborated upon here.

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[39] J. B. Littlefield, C. E. Brown, and H. H. Schrenk, *U. S. Bur. Mines Circ.* No. **6993,** 1938

4. Owen's Jet

The Owen's jet sampling device draws an air sample of 50 ml. or more through a moistening chamber and then at high velocity through a narrow slot, usually 1 cm. long and 0.1 cm. wide. The lowered temperature resulting from greatly reduced pressure on the air passing through the slot causes condensation of moisture on any dust particles and the droplets are impinged against a cover glass where they adhere and later dry, leaving the dust on the cover glass. The ribbon of dust thus formed is not uniform and is therefore difficult to count. It has all the disadvantages of the konimeter and is, further, susceptible to different efficiencies depending upon the rate of pull on the pump plunger. The instrument has a value for comparisons, as does the konimeter. The Bausch and Lomb dust counter is a modification of this device.

B. ELECTROSTATIC PRECIPITATION

The electrostatic precipitator has a high efficiency for collecting all types of particulate matter. This device utilizes the principle of the Cottrell precipitator whereby air is drawn through a tube within which is a central conductor wire electrode, the other electrode being formed by the tube or its conductor lining or covering. For the purpose of air sampling the tube diameter is usually between $1^1/_2$ and 3 inches and the voltage used ranges from 8000 to 30,000. The relationship of tube diameter, air flow, and voltage must be within certain limits in order to approach the maximum efficiency of 100 per cent. A commercially available portable outfit similar to one described by Barnes and Penney[40] operates on a 110-volt 60-cycle current producing under favorable circumstances a secondary voltage of 8000 to 15,000. It is important that this voltage be checked, and maintained at not less than 10,000. The precipitator is equipped with a fan and a flowmeter calibrated to draw approximately 3 cu. ft. of air per minute. This volume, likewise, should be checked by a suitable meter. The dust content of the air is deposited upon the inside of the precipitator tube or, in some instances, on the inner electrode. Any deposit should be carefully preserved and transported to a laboratory for weighing, counting, or chemical analysis. This device is especially useful for sampling fumes, smokes, or other suspended matter with a particle size below $^3/_4$ μ in diameter, in which range the impinger apparatus is not satisfactorily efficient. It is not suitable for use in flammable atmospheres.

As a comparison of efficiency between the standard impinger and the electrostatic precipitator for sampling fluoride fumes in a magnesium foundry, the following figures are of interest. With two impingers in series, from 62 to 87 per cent of the total amount collected was found in the first impinger and from 13 to 38 per cent in the second. On the average there was 74 per cent in the first and 26 per cent in the second. Samples collected simultaneously with a commercial electric precipitator (10,000 volts by spark-gap calibration) at the same location yielded from 80 to 106 per cent of the amount of fluorides found in the two impingers, the average being 90 per cent. The results indicate that the two impingers in series were 10 per cent more efficient than the precipitator for fluoride fume. No attempt was made to determine what percentage of the fluorides existed in the gaseous phase, but, inasmuch as some of the fluoride was disseminated into the air by contact of ammonium bifluoride with hot sand molds and molten magnesium, it is reasonable to suppose that some of the fluoride existed as hydrogen fluoride gas. This gas, of course, would not be caught by the precipitator, but some would be caught by the impingers, thus increasing their efficiency ratio and indicating a falsely high collection efficiency, when compared with that of the precipitator.

This precipitator has been found satisfactory for collecting silica dust samples for quantification by counting.[41] Another electrostatic collector for dusts for light-field counting techniques was devised by Barnes.[42] This device consists of an aluminum cylinder 9 inches in diameter and 12 inches long holding about $^1/_2$ cu. ft. of air. The ends can be closed with micarta disks that support an ionizing wire axially through the center of the cylinder. A slide adapter in the side of the cylinder holds a special microscope slide with conducting surface. In use, the cylinder is opened and moved to the sample location, the ends are closed, the slide is uncovered, and the dust is deposited electrostatically in about 15 seconds. Several samples can be taken on the same slide if desired. It has been stated that the device is nearly 100 per cent efficient and that the slide receives a uniformly distributed, proportionate share of the dust in the air in the cylinder at the time the current is turned on.

C. FILTRATION

Paper thimbles[43] have been used successfully for collecting various dusts, including explosives. They have a very high efficiency and at an air flow of 2 cu. ft. per minute have been found to collect nearly 100 per cent of most dusts and around 50 per cent of tobacco smoke. Filters made of salicylic acid,[44] sugar, or other material to be dissolved later in a liquid medium leaving the dust in suspension, have also been used. Filter-paper disks have been used for sampling: the blackening of the paper, after a measured volume of air has been drawn through, may be compared with standards; or the samples obtained may be used for counting, with results comparable to results obtained by the impinger method.[45] Large filter-paper[46] cups, with inverted cones, have been used for rapid sampling of particulate matter from large air volumes. Molecular (membrane) filters are useful for the collection and examination of aerosols. They are highly efficient for

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[40] E. C. Barnes and J. W. Penney, *J. Ind. Hyg. Toxicol.*, **20**, 259 (1938).

[41] H. H. Schrenk, *Am. J. Pub. Health*, **30**, 1183 (1940).

[42] E. C. Barnes, *Am. J. Pub. Health*, **26**, 274 (1936).

[43] L. T. Trostel and H. W. Frevert, *Ind. Eng. Chem.*, **15**, 232 (1923).

[44] F. R. Holden, W. C. L. Hemeon, and E. C. Hyatt, *Seventh Annual Meeting Amer. Ind. Hyg. Assoc.*, Chicago (1946).

[45] C. E. Brown, *U. S. Bur. Mines Rept. Invest.* No. **3788,** 1944.

[46] L. Silverman and C. R. Williams *J. Ind. Hyg. Toxicol.*, **28**, 21 (1946).

particles in the 0.1-μ range.[47] A high-efficiency large-volume sampler that collects smog particles from air at the rate of 1000 c.f.m. has been constructed.[48]

D. THERMAL PRECIPITATION

Green and Watson[49] devised a thermal precipitator that draws air by water displacement at about 7 ml. per minute through a 0.051 × 0.95 cm. slot. A nichrome wire 0.025 cm. in diameter, heated to 100° C., is held centrally in the slot and the walls of the slot are cover slips backed by brass blocks for cooling. As the air passes between the hot wire and the cool surface of the cover glass any suspended dust particles are deposited upon the cover slips. The efficiency of the device is said to be 100 per cent. The deposit is suitable for microscopic examination. One technique includes counts and particle-size determinations with the electron microscope.[50]

E. SEDIMENTATION

The sedimentation cell, as devised by Green,[51] is a brass cylinder 6 cm. deep and 3.6 cm. in diameter closed at the top with a swivel lid and at the bottom by a brass slide mounting two $^1/_2$-inch cover slips. The cylinder is filled with atmosphere and then closed at the point where the sample is desired, and left to stand 1 to 3 hours. Then the cover slips are removed and examined under a microscope with high resolving power. The method is suitable for determining the count and particle size of dusts down to 0.2 μ in diameter (3 hours settling time). The sedimentation cell is intended as a laboratory or research instrument and not for field use.

II. Evaluation of Dust Samples

The evaluation of a dust sample may be made on a weight basis, with or without the aid of chemical analyses, or it may be accomplished for all insoluble pneumoconioses-producing and nuisance dusts by determining the number of particles in a measured volume of air.

After dust particles from a known volume of air are collected, an aliquot portion must be counted in order to compute the number of particles suspended in a cubic foot of the atmosphere sampled, the cubic foot being the accepted unit for comparison in the United States.

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[47] D. A. Fraser, *Arch. Ind. Hyg. and Occupational Med.,* **8,** 412 (1953). M. W. First and L. Silverman, *Arch. Ind. Hyg. and Occupational Med.,* **7,** 1 (1953).

[48] G. C. Clayton, J. R. Arnold, and F. A. Patty, *Science,* **122,** 751 (1955), and *Am. Ind. Hyg. Assoc. Quart.,* **16,** 293 (1955).

[49] H. L. Green and H. H. Watson, *Med. Research Council, Special Reprint* No. **199,** H. M. Stationery Office, London, 1935.

[50] J. H. L. Watson, *Can. J. Research,* **21,** 89 (1943).

[51] H. L. Green, *J. Ind. Hyg. Toxicol.,* **16,** 29 (1934).

A. MAKING A DUST COUNT

1. Counting Impinger Samples

Dilution of Sample. Impinger samples are diluted, either in the impinger flask or in a volumetric flask, with dust-free distilled water or other sampling medium to a definite volume, which will depend upon the size of the sample, the dust concentration, and the method of counting to be employed.

Counts of 20 to 75 per fourth of the ruled field of the Whipple disk are held to be most satisfactory; though, with a carefully prepared dust-free sampling medium, properly cleaned cells, and careful handling of samples and controls, it is practical to make counts of less than 20 per quarter field. If necessary, the sampling media should be redistilled in glass until counts of not more than 3 or possibly 4 per quarter field are obtained. Samples giving counts of over 100 per quarter field usually warrant dilution. If the microprojector is to be used, counts of 5 to 250 particles per 0.05 cu. mm. are practical; for cells of 1-mm. depth, a 10 × 50 cm. strip of screen at 1000x magnification is the equivalent of 0.05 cu. mm.

Choice of Counting Chamber and Method of Cleaning. There have been many heated condemnations and defenses of special types of counting chambers. The majority of persons prefer those of 1-mm. depth, but individual tastes differ and much outstanding work has been done using cells of 0.1- and 0.25-mm. depth. Where liquids other than water are to be used, fused cells are more satisfactory than cemented cells. One objection to the Sedgwick-Rafter cell, that of the difficulty of cleaning, is easily overcome by the use of a good aqueous soap solution to which meta- and pyrophosphates have been added. (Either "Calgon" and soap solution or "Calgonite" is a very satisfactory cleaning agent of this type for counting chambers.) After the cells are cleaned they should be rinsed with dust-free distilled water, followed by alcohol, if desired. They are then drained and wiped dry with lens paper or a clean, lint-free cloth (preferably linen, though some analysts use other materials, such as silk). In some laboratories, the drained cells are dried in an oven. A camel's-hair brush has been recommended for brushing out cells after drying, but the success of this procedure is open to question. Some persons allow counting cells to stand in a covered container of clean alcohol until wanted for use, while others prefer to dry them and keep them wrapped in lens paper or cloth. If the cleaning routine is carried out just prior to the use of the cells, the possibility of contamination with dust is lessened.

The majority of our standards have been based upon impinger samples collected in water, and counts made in cells 1 mm. deep after 20 minutes settling time. For most inorganic dusts the count in 1-mm. cells increases with settling time rather rapidly during the first 20 to 30 minutes and more gradually, but consistently, for hours thereafter. The increase in count during the first 20 minutes is so rapid as to make results taken during this period of little value. Except for the fact that 20 minutes has been the accepted settling time, counts made after 30 to 45 minutes settling would be more comparable, because the rate of increase is less than at 20 minutes. When using propyl, isopropyl, or butyl alcohol as the collecting medium, 30 minutes settling time is thought to be comparable to 20 minutes with water. Cells of less than 1-mm. depth give higher results with similar settling time or the same results with shorter settling time. When the dusts have a density less than, or even approaching, that of the collecting liquid, it is impossible to count all particles in any cell without racking from top to bottom.

Filling the Cell and Preparation for Counting. The dust suspension is agitated and a sample sufficient to fill the counting cell is transferred, usually by pipet, into a clean Sedgwick-Rafter cell, Dunn cell, or other suitable counting chamber of accurately controlled depth, which may be from 0.1 to 1.0 mm. (It is evident that an error in cell depth of 0.1 mm. on a 1-mm. cell introduces an error of 10 per cent. Many of the cells supplied by manufacturers have been proved by measurement to be 10 to 40 per cent oversize.) It is neither necessary nor desirable to filter the suspension through a 325-mesh screen as was formerly the recommended practice. If leakage or evaporation is found to occur when alcohol is the sampling medium and the Dunn cell is used for counting, a thin film of dust-free liquid petrolatum between the glass surfaces will prevent the difficulty.

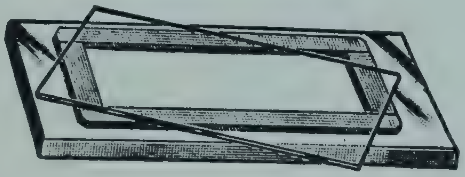

Figure 5. Sedgwick-Rafter cell.

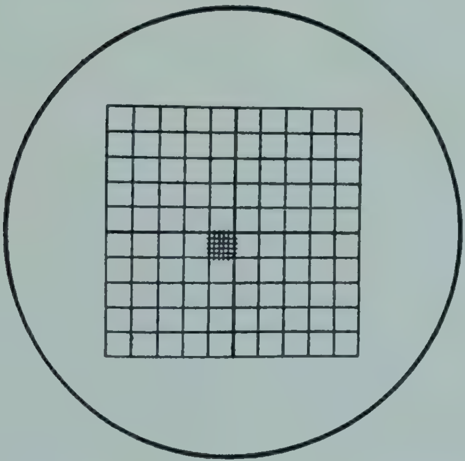

Figure 6. Ruling of Whipple ocular micrometer disk.

Microscopic Arrangement for Light-Field Counting. For light-field counting, our present accepted standard, the amount of light used should be adjusted to prevent glare, but actual shading, tilting of the mirror, and the use of spotted cells or blue filters must be tempered with caution, else a grossly erroneous count lying between the true light-field and dark-field counts may be obtained. The usual microscopic arrangement includes a 16-mm. objective and a 7.5*x* ocular containing a Whipple disk, the tube length being adjusted so that the Whipple disk exactly subtends 1 sq. mm. of the floor of the counting cell. This adjustment is made by the use of a stage micrometer.

Method of Making and Computing Counts. The recommended practice for counting is to prepare two cells from each dust sample and to count one fourth of the ruled field of the Whipple disk in five well-separated representative locations of each cell. The ten counts are averaged and from this is subtracted a similarly obtained count of a control sample of the collecting liquid through which no air has been drawn. The control count compensates for dust acquired in manipulation, as well as dust in the sampling medium or the microscopic system. This average net count per fourth of the field is then computed to million particles per cubic foot in the sampled atmosphere, taking into account air volume sampled and volume of impinger liquid.

$$\text{Particles per cu. ft.} = \frac{\text{count per fourth of field} \times 4 \times 1000 \times \text{ml. of sample liquid}}{\text{cu. ft. of air sampled}}$$

There is considerable variation in the manner of making dilutions and filling cells, the length of settling time, the choice of a counting cell, and the miscroscopic system employed; therefore to expect greater correlation than ±10 per cent between two independent counts is to be overly optimistic, and variations of over 50 per cent are not uncommon. Despite all of these objections our present system of evaluation is not to be condemned, but we should encourage research into better methods and be mindful of the folly of evaluations based upon a single dust count. We should avoid the idea that the threshold limits of dustiness now accepted are absolute figures rigidly separating safe atmospheres from dangerous ones. Rather, they should be regarded as bench marks of desirable control.

Dark-Field versus Light-Field Counting. Dark-field illumination obtained by means of a Zeiss "Dissecting Condenser" and counts made with a microscopic system employing a 16-mm. achromatic objective with N.A. = 0.2 (8*x*), a 30*x* ocular, and a tube length adjusted to give a magnification of 250*x* have been shown to yield results from 2 times to more than 50 times as high as those obtained by standard light-field technique.[52] The limit of visibility of this arrangement is about 0.1 μ. The ratio of DF count to LF count increases with an increasing proportion of particles less than 0.7 μ in diameter and is an indication of particle size. This does not necessarily indicate that the dark-field count is a better index, or even that it would be after the establishment of sufficient correlation between lung damage and dustiness determined by such dark-field counts. Although impinger samples are more easily counted by the dark-field technique, and with much higher results, the collection efficiency of the impinger as now used drops so rapidly with diminishing particle size, for particles below $^3/_4$ μ, that the advantage in counting may be more than offset by decreasing efficiency of collection. Our present method of evaluation is largely limited to those particles above 0.7 μ in diameter: whether this gives rise to serious errors remains to be proved. It has been suggested that particle size may be a factor in explaining the relatively low light-field counts found in the silica brick industry in work atmospheres where silicosis is known to occur. It would seem desirable to collect samples in this and some other silica exposures and, after evaluation of all particles in the range between 0.1 and 5.0 μ, make a statistical study in an effort to illuminate the effect of the smaller particles as well as possibly to explain the incidence of silicosis in silica brick manufacture.[53]

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[52] T. Hatch and C. L. Pool, *J. Ind. Hyg. Toxicol.*, **16**, 177 (1934).

The Microprojector. The microprojector[54] furnishes a useful variation in counting methods for evaluating impinger samples, whereby the dust image is projected, usually at a magnification of 1000 diameters, onto a ruled screen. A 16-mm. objective is used and the increased magnification is obtained by employing higher power in the ocular and by projection. Two cells are prepared and each is counted by counting all the particles in five well-separated representative fields of 0.05 cu. mm. each (10 × 50 cm. strip on the screen, at 1000*x*). A similar count of the control is then subtracted from the average of the counts on the two sample cells, and the final computation is as follows:

$$\text{Particles per cu. ft. of air} = \frac{\text{count in 0.25 cu. mm.} \times 4 \times 1000 \times \text{ml. of dust suspension}}{\text{cu. ft. of air sampled}}$$

The microprojector can be used for both counts and particle-size determinations, does not cause excessive eye strain, and, at least among the inexperienced, tends to promote closer agreement and reproducibility of counts. It is probably not a time saver when counts are being made by one individual. With direct counting through a microscope, the analyst can arrange all his material within arm's length and not spend time opening and closing the viewing booth door and walking from booth to microscope to adjust the light source and to fill cells and place them on the stage. The time gained with the microprojector in avoiding secondary dilution of some samples does not compensate for this loss. The microprojector is, however, very useful for counting as well as for particle size determination, yields dependable and reproducible results, and is an interesting and valuable demonstration piece. The midget counterpart[55] requires less space and obviates the necessity for remote controls to manipulate focusing and mechanical-stage controls.

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[53] W. B. Fulton, F. E. Butters, A. E. Dooley, F. B. Koppenhaver, J. L. Matthes, and R. M. Kirk, *A Study of Silicosis in the Silica Brick Industry*. Bur. of Ind. Hyg., Dept. of Health, Harrisburg, Pa., 1941.

[54] C. E. Brown, L. A. Baum, W. P. Yant, and H. H. Schrenk, *U. S. Bur. Mines Rept. Invest.* No. **3373**, 1938.

[55] C. E. Brown, *U. S. Bur. Mines Rept. Invest.* No. **3780**, 1944.

2. Counting Konimeter Samples

Konimeter samples may be examined and counted by use of the special microscope attached to some konimeters. More satisfactory counts are obtained by using a regular microscope with light-field illumination and fitted with a special holder so that the konimeter dust spots can be rotated and any one can be brought into view readily. A satisfactory magnification has been found to be 200*x* obtained by using a 10*x* objective with a compensated 20*x* ocular. The ocular is fitted with a squared micrometer scale, similar to that shown in Figure 7, with two crossed lines that outline sectors of 18 degrees. The parallel lines *ai* and *id* are for use in estimating the size of particles. In counting, the scale is centered over the dust spot and all the particles in the two 18-degree sectors are counted, giving a total count of all the dust in 36 degrees or 10 per cent of the entire spot. From this count must be subtracted a control count of an equal area of the unused plate and adhesive film. The net count of 10 per cent of the total area of the dust spot is multiplied by 10 and divided by the volume of air sampled (in milliliters) to obtain the number of particles per milliliter. If the results are desired in million particles per cubic foot, the number of particles per milliliter may be multiplied by 0.02832; for a 2.5-ml. sample the actual count for a 36-degree sector may be multiplied by 0.113; and for a 5-ml. sample, the 36-degree sector count should be multiplied by 0.057.

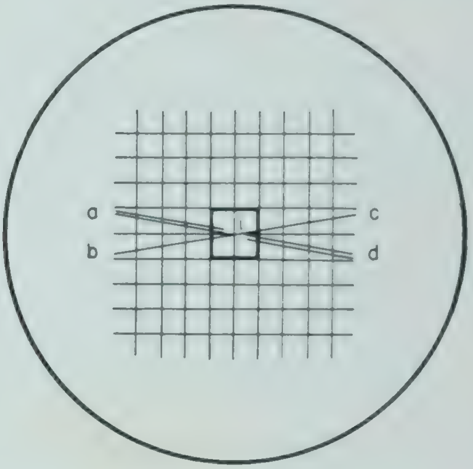

Figure 7. Micrometer scale for counting konimeter samples.

3. Counting Owen's Jet Samples

The cover slip with dust deposit is mounted dry with dust side down on a microscope slide and examined under a microscope with an oil immersion objective, dark-field illumination, and about 1000*x* magnification. An ocular with a crossbar ruled micrometer with 1-mm. squares is used; a representative band of one square width across the ribbon of dust is selected, and all the particles in this band are counted. Two or more bands may be counted and averaged if desired, but the effort is hardly justifiable because the ribbon is rarely uniform in distribution or width throughout its length, especially at each end. The number of bands in the length of sample ribbon must then be determined if this factor has not previously been established. Lower magnification must be used to measure the ribbon in terms of the ruled ocular disk and the relation between objectives, if not known, can be established by the use of a stage micrometer. Since the volume of air sampled was 50 ml., the number of particles per milliliter is computed by multiplying the number found in one band by the number of bands and dividing by 50. This result may easily be computed to million particles per cubic foot by multiplying it by 0.028, but no correlation with standard impinger results should be assumed from such computation.

B. DETERMINING PARTICLE SIZE DISTRIBUTION

Use of the microprojector[54,56] is perhaps the most satisfactory method of determining the particle-size distribution of dust samples collected either by the impinger (one or more drops evaporated to dryness on a slide), the konimeter, the Owen's jet, or the electric precipitator. While a magnification of 1000 diameters (employing 10*x* objective) is ordinarily used for counting, a magnification of 10,000 diameters (90*x* oil-immersion objective) is recommended for determining the particle size, a change in tube length being necessary to adjust the magnification. Particle-size distribution is determined by estimating the size of each of the particles in representative fields of the sample using the 0.5-μ squares on the screen for comparison. The particles are classified according to diameter in intervals of each 0.5 μ, counts for each class being registered on a Marbel blood counter, or by other suitable means. The number of particles of a particular size that occur in a given count determines that size frequency. These frequencies are usually expressed in percentages of the total count.

The data from a particle-size determination may be presented graphically, as in Figure 8, by plotting the counts as ordinates against the sizes as abscissas at regularly spaced size intervals. This graph clearly illustrates the size variation and counts and shows two typical frequency distributions.

When particle-size data are tabulated, as in Table 4, which has size groups at 0.5-μ intervals and frequencies in percentage, it is again possible to compare the characteristics of different dust dispersions. The median is the cumulative 50 per cent size, usually a representative measure of average dust size. It should be noted, however, that in the case of some dusts with wide variations in size the mode may prove not to coincide with the median, and would be a better measure of central tendency: aluminum dust, soapstone dust, and slate milling, in all of which the mode, value of most frequent occurrence, is 1.25 μ, although the medians range

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[56] C. E. Brown and W. P. Yant, *U. S. Bur. Mines Rept. Invest.* No. **3289,** 1935.

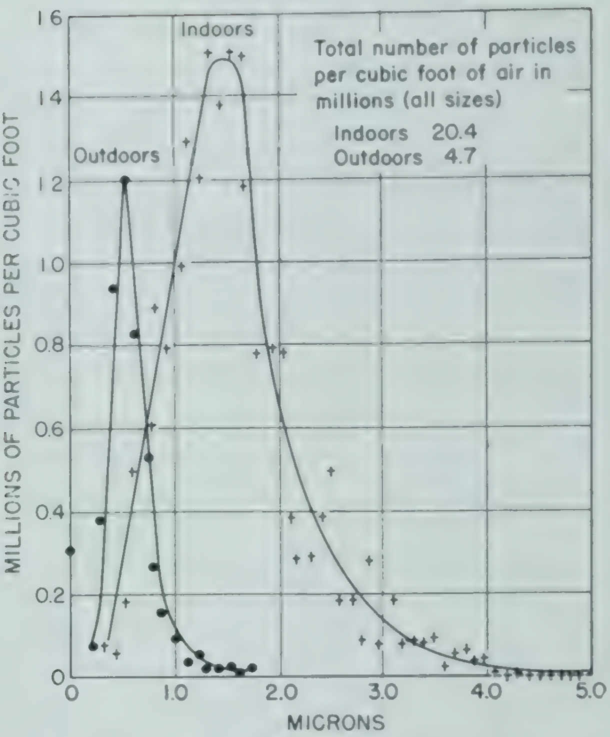

Figure 8. Graphic illustration of size distribution of indoor and outdoor dust at granite cutting plants.

TABLE 4

Size-Frequency Distribution of Various Industrial Dusts as Compared to Outdoor Dust[57]

Kind of dust	Number of samples	Median	Average frequency in per cent (size group in microns)											
			0 to 0.49	0.5 to 0.99	1.0 to 1.49	1.5 to 1.99	2.0 to 2.49	2.5 to 2.99	3.0 to 3.49	3.5 to 3.99	4.0 to 4.49	4.5 to 4.99	5.0 to 5.49	5.5 to 5.99
Outdoor dust	179	0.5	56.0	41.0	2.5	0.5	....	....	....	....	....	....	....	....
Sandblasting	9	1.4	1.4	19.7	34.7	20.3	12.6	5.2	2.8	1.6	1.1	0.2	0.2	0.2
Granite cutting	4	1.4	2.0	19.0	33.6	24.5	10.4	4.6	3.1	0.6	0.9	0.3	1.0	....
Trap rock milling:														
Crusher house	1	1.4	0	13.0	39.0	33.0	10.5	2.5	2.0	....	....	....	....	....
Screen house	1	1.3	2.0	31.5	33.0	16.0	10.0	4.5	2.5	0.5	....	....	....	....
Disk crusher	1	0.9	10.0	48.0	31.0	6.0	3.0	1.0	1.0	....	....	....	....	....
Foundry parting compound	2	1.4	0.5	22.0	42.0	17.3	9.2	5.0	1.5	2.0	0.5	....	....	....
General foundry air	1	1.2	0	26.0	48.0	17.0	8.0	1.0	....	....	....	....	....	....
Talc milling	1	1.5	0	16.0	32.0	20.0	13.0	7.0	5.0	2.0	2.0	2.0	0	1.0
Slate milling	1	1.7	1.0	13.0	29.0	17.0	14.0	14.0	6.0	4.0	1.0	0	1.0	
Marble cutting	1	1.5	0	12.0	37.0	21.0	10.0	11.0	3.0	0	1.0	2.0	2.0	1.0
Soapstone dust	2	2.4	1.2	16.0	19.0	13.0	11.0	6.0	6.5	4.5	5.5	3.3	2.5	11.5
Aluminum dust	1	2.2	3.0	8.0	20.5	14.0	11.5	9.0	6.5	3.0	3.5	4.0	7.0	10.0
Bronze dust	1	1.5	1.0	12.0	33.5	25.0	21.0	6.0	1.5					

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[57] J. J. Bloomfield, *U. S. Pub. Health Repts.*, **48**, 961 (1933).

from 1.7 to 2.4 μ and in each case represent much smaller frequencies than the modal ones.

Still another method of treating the data is to plot the cumulative percentage of particles for the different class intervals, percentage less than a stated size, against the size on logarithmic probability paper[58] and draw the best straight line through the points. From this line, which assumes a normal probability distribution, the geometric mean[59] is observed as the 50 per cent size and the standard geometric deviation readily computed by dividing the 84.13 per cent size by the 50 per cent size. As an example of this treatment, the screen-house sample from a traprock mill has been taken from Table 4 and plotted on logarithmic probability paper and the parameters determined in Figure 9.

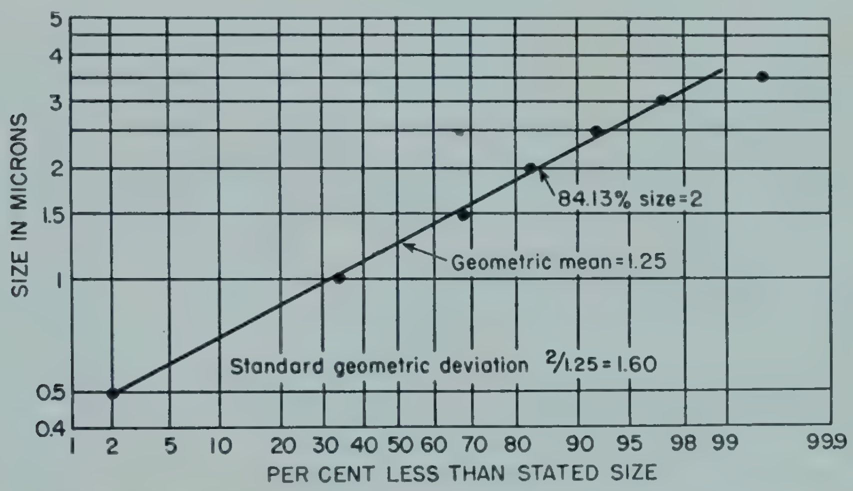

Figure 9. Logarithmic probability plot of data on screen house taken from Table 4.

Results similar to those given by the microprojector are obtained by the use of the filar micrometer eyepiece at a magnification of 1000 diameters, but in this instance several representative fields are chosen and the diameters of the first 200 particles encountered in each are measured by moving the cross hair across the field from left to right.

A particle-size estimation of dusts can be made by the use of a photomicrograph, which has the advantage of being a permanent visual record.

In any of these methods the results are only relative. The optical systems employed fail to resolve particles appreciably smaller than 0.5 μ and, since it has been demonstrated that dusts have widely varying proportions of particles below this size, it is evident that the absolute average particle size is necessarily less than the determined value. Since the significant size range of dusts injurious to health is now believed to be below 3 μ, with an as yet undetermined lower limit of significant size, this factor of unresolved particles may be of considerable importance.

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[58] P. Drinker, *J. Ind. Hyg.*, **7**, 305 (1925).

[59] P. Drinker and T. Hatch, *Industrial Dust.* McGraw-Hill, New York, 1936.

Holden and Hyatt[60] propose that in the evaluation of exposures to dusts containing free silica, a sufficiently large sample of air-borne dust be collected and sized by allowing the suspension in alcohol to settle for a measured time. The larger particles settle out leaving in suspension the particles 5 μ or less in diameter; the silica content of this latter fraction is determined in order to appraise the relevant silica dust exposure.

C. WEIGHING THE SAMPLE

It is possible to evaluate certain classes of particulate samples by weight. This may be true of impinger samples (especially useful with soluble dusts) as well as samples collected by filtration or by electrostatic precipitation. In this manner the milligrams of toxic contaminants per cubic meter of air may be determined, and by ignition the sample may be divided into combustible and incombustible matter. Bloomfield and DallaValle,[61] by weighing 611 impinger samples upon which counts had been made, found a certain amount of correlation between the weight and count, as given in Table 5. Since particle-size distribution is a tremendous factor to be considered in any attempt to evaluate weight or count in terms of the other, in most cases such a conversion is not practical, and if attempted is apt to be translated into erroneous conclusions.

TABLE 5

Correlation between Particle Counts and Weights of Air-Borne Industrial Dusts

Kind of dust	Coefficient of correlation	Millions of dust particles equivalent to 1 mg.
Bituminous coal	0.847	31
Anthracite coal	0.771	44
Granite	0.755	31
Metal grinding and polishing	0.698	19
Cement	0.694	15
All dusts	0.726	35

D. ANALYZING THE DUST

1. *Chemical Analysis for Toxic Materials*

Dusts collected by the impinger, the paper thimble or other filtration medium, or the electric precipitator may be analyzed by chemical methods, due consideration being given to the amount of sample in relation to the sensitivity and precision of the method. Methods of analysis for the toxic elements, metals and nonmetals, will be discussed individually in Volume II of this book. Differentiation of free silica (SiO_2) from silicates cannot be accomplished satisfactorily by chemical means. However, the quartz content of dusts containing representative particles 10 μ or more in diameter may be satisfactorily determined in samples greater than 0.1 g. by combining chemical and petrographic techniques. For such samples to be truly representative of an exposure they should be collected in the breathing zone of the workman. Nevertheless, ledge or rafter samples are not to be entirely scorned, and when selected with due consideration to obtaining air-borne rather than projected or sifted deposits, they offer useful information regarding exposures, frequently more reliable than the analysis of unselected deposits or unprocessed material.

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[60] F. R. Holden and E. C. Hyatt, *Annual Meeting Ind. Hyg. Foundation Amer.*, Pittsburgh (1945).

[61] J. J. Bloomfield and J. M. DallaValle, *U. S. Pub. Health Bull.* No. **217** (1935).

2. Determination of Quartz

By Combined Chemical and Petrographic Analysis. If one is interested only in the determination of free silica, especially quartz, in a sample of dust ranging in size to 10 μ or greater, it is only necessary to clean the dust, removing as much as possible of particles other than free silica, and to estimate the free silica in the residue by the use of petrographic methods. The procedure may be simplified and standardized as follows. A portion of the dust, between 0.1000 and 0.5000 g., is weighed. If considerable organic matter is present the weighed sample should first be ignited, otherwise it is placed directly in a pyrex beaker and 30 ml. of concentrated hydrochloric acid plus 10 ml. of concentrated nitric acid are added. The contents of the beaker are heated to boiling on a hot plate for 20 minutes, diluted with about 200 ml. of hot water, heated to boiling, filtered through No. 42 Whatman filter paper, and washed with hot water. The paper and residue are then transferred to a weighed crucible, dried, ignited at about 600° C. until the carbon has disappeared, cooled, and weighed. To examine the residue with a petrographic microscope, a few particles are transferred to a microscope slide by means of a dissecting needle, a drop of immersion oil of n_D 1.545 is placed on the specimen, and it is covered with a cover slip.

A series of immersion oils may be prepared covering the refractive index range of 1.46 to 1.62 by mixing light refined paraffin oil (1.46) with monochloronaphthalene (1.62). Similarly monobromonaphthalene (1.65) may be used. If the refractive index of each constituent oil is multiplied by the percentage of that oil present, and those products are added, the sum will be approximately the refractive index of the mixture. The oils should be thoroughly mixed and the refractive index at 25° C. determined by means of an Abbe refractometer.

The specimen is examined at about $450x$ magnification: a $45x$ objective and $10x$ cross-hair ocular have proved very satisfactory. Should the particles be large enough to be identified as quartz, diatomaceous earth, chalcedony, cristobalite, or other form of free silica, or an easily estimated mixture of these with other material, the calculation may be completed by counting or estimating particles in representative fields. A $14.3x$ objective is very useful for such estimation. If the mixture contains, or is suspected of containing, feldspars (silicates) or other minerals readily confused with quartz, it is necessary to purify it further. To accomplish this, about 10 ml. of hydrofluosilicic or fluoboric acid is poured on the sample in a small platinum crucible and it is set aside for 3 to 6 days, being stirred at least twice each day with a platinum loop. At the end of the 3 to 6 days, depending upon the gross appearance of the residue, the remaining dust is filtered off, washed, dried, ignited, and weighed. It is again inspected under the petrographic microscope in order to determine the nature and purity of the residue, which should now be quartz or possibly other forms of free silica, such as chalcedony, tripoli, cristobalite, and tridymite, which dissolve in the above acids slowly, or one of a few other minerals such as silicon carbide, which is not removed by these combined acid treatments but is readily distinguishable. The petrographic identification of minerals is far beyond the scope of this chapter but a simple procedure for the identification of the quartz content of dusts, utilizing petrographic technique, may be stated as follows.

Place a minute amount (few particles) of the dust residue on a microscope slide, add a drop of immersion oil of refractive index 1.545, and cover with a cover slip. Observe with a petrographic microscope using crossed Nicols under about 450*x* magnification. If quartz is present the small particles will appear as milky white irregular shapes. To determine whether an individual particle is quartz, use the crossed Nicols, rotate the stage, and observe that quartz particles (except when oriented with optic axis vertical) disappear four times per complete revolution of the stage. This characteristic establishes that quartz particles are anisotropic as distinguished from isotropic crystals, which are invisible when viewed with crossed Nicols. Bring the stage to rest with a particle extinguished, then slide the analyzer Nicol prism out of the system, focus on the edges of the crystal, and raise the microscope tube from focus. A light halo surrounding the particle will move into or away from the crystal depending upon its orientation, because this halo (Becke line) always moves toward the medium of higher refractive index when the microscope tube is raised from focus. Now turn the stage exactly 90 degrees in either direction and repeat this procedure. If the particle is quartz the halo of light will move in the opposite direction. This is true because quartz has two indices of refraction, 1.544 and 1.553, both close to, and one on each side of, 1.545, the refractive index of the immersion oil. The refractive index of a submerged crystal may be judged to be very near that of the immersion oil if there is a lack of clear distinction of boundary lines; this occurs when the difference in refractive indices is less than 0.01. When the difference is less than 0.001 a submerged crystal can be seen only with difficulty. If the particle under examination fits these characteristics, that is, irregular shaped, milky white between crossed Nicols, two refractive indices one just above and one barely below 1.545, it may be suspected of being quartz. It is good practice to check a sample now with oil of n_D 1.57 to make certain that the crystals have both indices less than 1.57.

The identity of the crystals may be verified by further scrutiny. Center a particle exactly under the cross hairs and align the microscope system so that the particle does not move from position during a complete revolution of the stage. Now, by means of a Wright's diaphragm—or less satisfactorily with the Bertrand lens, if the microscope is so equipped, and no Wright's diaphragm is available—isolate this crystal and observe its inference figure.[62] This test cannot be applied successfully to particles appreciably smaller than 10 μ in diameter. It is done with crossed Nicols and upper lens condenser (converger) swung into place. Upon rotation of the stage a black cross on a light field, or portions of the arms of a cross, can be seen (interference figure for uniaxial crystal). If only portions of the arms making up the cross are visible, the analyst must imagine the complete figure in order to choose the section he wishes to investigate (see Figure 10).

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[62] E. E. Wahlstrom, *Optical Crystallography*. Wiley, New York, 1943.

A crystal is rarely found oriented so that the cross is in the center of the field, as in 1 (optic axis figure); infrequently, with the axis of the cross visible at or near the circumference of the field, as in 2; but usually, as in 3, where only the arms of the cross, appearing as straight or very slightly curved bars extending perpendicular to the observer, move straight across the field from left to right, or vice versa, or extending horizontal, move from top to bottom, or vice versa. The crystal may now be further classified as positive or negative by the use of a quartz wedge, mica plate, or selenite plate. First choose the lower right quadrant, if only the arms (bars) are visible, by rotating the stage until a horizontal bar has passed across the field away from the observer and a perpendicular bar is just out of view to the left. Now, as a quartz wedge is inserted into its slot as a bisector of this field, color curves will move outward if the particle is quartz (positive). With a mica plate so inserted, a black dot will appear in this and in the upper left quadrant, while with a selenite plate these same areas (3 to 6, and 9 to 12 o'clock, respectively) will have a yellow tinge and the other 2 quadrants will appear blue. With negative crystals opposite results are obtained. The particle that has met these requirements may now be definitely identified as quartz because it has been found to be anisotropic, uniaxial, positive, with indices of refraction of barely less than 1.545 (1.544) and between 1.545 and 1.57 (1.553). No other crystalline material fits all of these characteristics.

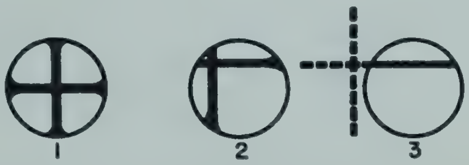

Figure 10. Interference figures of uniaxial crystals (quartz).

If the sample on first observation is found to contain a large percentage of particles other than quartz (feldspars and other silicates), it is then necessary to treat with hydrofluosilicic acid. After treatment the residue is again examined and if found to be quartz a correction of 0.7 per cent per day should be added to the quartz residue to compensate for its slight solubility in hydrofluosilicic acid.

Other forms of free silica as well as all other minerals may be similarly identified by the petrographic microscope. Anyone interested in this method of identification should obtain samples[63] of each mineral he wishes to be able to identify, pulverize some of each in a diamond mortar, and practice with known pure materials until all of these characteristics are readily recognized. With the aid of samples and a table for the determination of minerals,[64] along with a few good texts,[65] the field may be broadened to include many minerals.

Impinger samples ordinarily do not have a sufficient number of particles 10 μ in diameter or larger upon which an interference figure can be obtained, and

[63] Ward's Natural Science Establishment Inc., Rochester, N. Y.

[64] E. S. Larsen and H. Berman, *U. S. Geol. Survey Bull.* No. **848** (1934).

[65] M. N. Short, *U. S. Geol. Survey Bull.* No. **914**, 1940. A. N. Winchell, *Elements of Optical Mineralogy*. Wiley, New York, 1931. A. N. Winchell, *Artificial Inorganic Solid Substances or Artificial Minerals*. Wiley, New York, 1931. E. S. Dana, *A Textbook of Mineralogy*. Wiley, New York, 1932. E. M. Chamot and C. W. Mason, *Handbook of Chemical Microscopy*. 2nd ed., Wiley, New York, 1938.

therefore any petrographic method applied to them must depend largely, if not entirely, upon refractive indices. Such methods[66] do not differentiate between quartz and other minerals of the same or similar refractive index, such as the feldspars, mica, talc, and some other minerals frequently found associated with quartz. They are intended to be rough estimates only, and give a maximum value rather than a true quartz value. However, in many situations a knowledge of the composition of the minerals from which the dust was generated can be used advantageously and can give the maximum estimate the status of a true value by ruling out any interfering minerals in the same refractive index range that are known not to be present.

By X-ray Diffraction. Where all of the dust particles are less than 5 μ in diameter, the only successful means so far devised of determining the crystalline, free silica content is by means of x-ray diffraction. When x-rays strike an object, some of the rays are diffracted. If the x-rays are monochromatic and a beam of parallel rays is directed at a finely powdered pure material, this diffraction assumes a characteristic and reproducible pattern that can be registered as lines on a photographic film (Figure 11). The rays that pass directly through the powdered substance provide a reference mark. This same material, whether in its pure state or mixed with other matter, will reproduce the same pattern even though many other lines may be produced by other constituents in the mixture. The pattern then serves as a reliable identification, which is thought to depend upon crystalline structure.[67] The density of the lines in the diffraction pattern of any substance

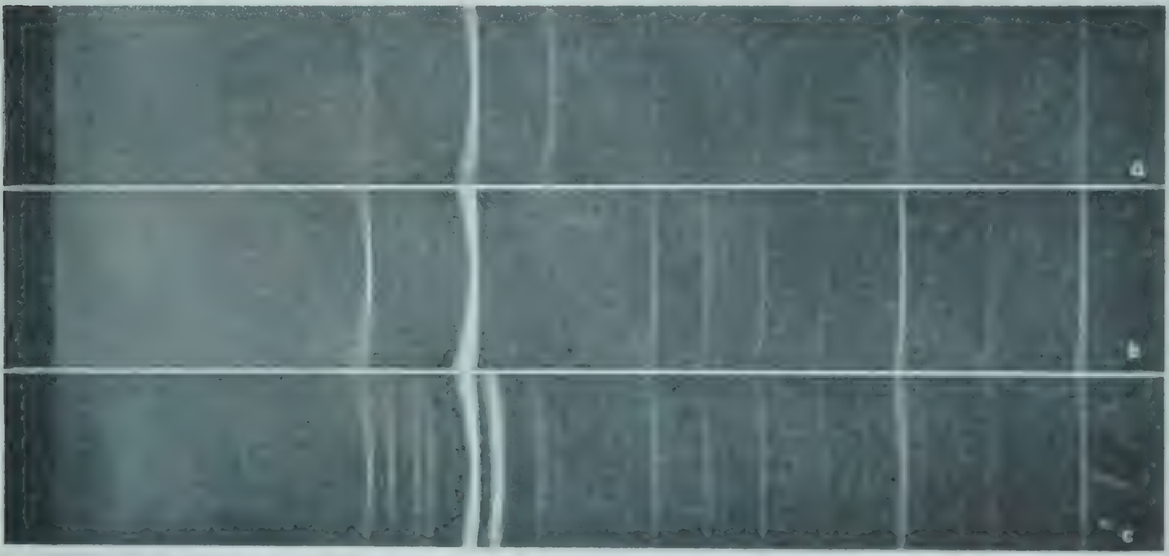

Figure 11. X-ray diffraction patterns of (*a*) quartz in dolomite, (*b*) pure quartz, and (*c*) quartz in albite. (Courtesy H. H. Schrenk, U. S. Bureau of Mines.)

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[66] H. L. Ross and F. W. Sehl, *Ind. Eng. Chem., Anal. Ed.*, **7**, 30 (1935); W. D. Foster and H. H. Schrenk, *U. S. Bur. Mines Rept. Invest.* No. **3368**, 1938.

[67] J. D. Hanolvalt, H. W. Rinn and L. K. Freval, *Ind. Eng. Chem., Anal. Ed.*, **10**, 457 (1938).

depends upon the amount of that substance in the sample. Quartz has four lines that are sufficiently intense for quantitative measurement. By the use of an internal standard[68] and a microphotometer for measuring the relative density of the lines of the unknown and those of the internal standard, quantitative measurements of satisfactory accuracy may be obtained.[69] For good results, samples for analysis must be ground to 200 mesh or smaller, and after the internal standard has been added the sample must be further ground and mixed. A special type of stainless steel ball mill, using methanol as a dispersing agent, has been used for this purpose, being operated 24 hours.

A recent development has been the advantageous use of Geiger counter spectrometers for determining the densities of the lines in the diffraction pattern, with better resolution in some instances of partial overlapping of lines, and, in some cases, obviating the need for an internal standard.

BACTERIA AND OTHER MICROORGANISMS

The sampling and evaluation of microorganisms in the atmosphere have received much attention in recent years, but the procedures are still in an experimental stage. There are several collection methods that employ the principle of impingement, such as the air centrifuge,[70] the funnel device,[71] the slit impinger,[72] Sharf's prescription bottle sampler,[73] the sieve device,[74] and the exposed agar plate or petri dish method. Simple Folin scrubbers,[75] beaded scrubbers,[76] and atomizer scrubbers[77] have also been used, and they give much higher results than methods that collect the microorganisms on a solid surface. The size of the organisms and their tendency to form clusters or clumps have an important bearing on the relative collection efficiency of a method. With the scrubbing devices any clumps or clusters are broken up, whereas they may register as one colony by impingement. Discussions of these devices including a comparison of their performances have been published.[78]

The sampling media[79] have a still greater influence upon results, not only as regards standard practice, in order to try to establish some means of comparison of results, but of even more importance, as regards the retention and growth of pathogenic organisms of interest in air sanitation work, and the inhibition of nonsignificant saprophytes that interfere with the desired bacterial counts.

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[68] J. W. Ballard, H. I. Oshry and H. H. Schrenk, *U. S. Bur. Mines Rept. Invest.* No. **3520,** 1940.

[69] J. W. Ballard and H. H. Schrenk, *U. S. Bur. Mines Rept. Invest.* No. **3888,** 1946.

[70] W. F. Wells, *Am. J. Pub. Health,* **23,** 58 (1933).

[71] A. Hollaender and J. M. DallaValle, *U. S. Pub. Health Repts.,* **54,** 574 (1939).

[72] R. B. Bourdillon, O. M. Lidwell, and J. C. Thomas, *J. Hyg.,* **41,** 197 (1941).

[73] R. Schneiter, A. Hollaender, B. Caminita, R. W. Kolb, H. F. Fraser, H. du Buy, P. A Neal, and H. B. Rosenblum, *Am. J. Hyg.,* **40,** 136 (1944).

[74] H. G. du Buy and L. R. Crisp, *U. S. Pub. Health Repts.,* **59,** 829 (1944).

[75] L. F. Rettger, *J. Med. Research,* **22,** 461 (1910).

[76] S. M. Wheeler, G. E. Foley, and T. D. Jones, *Science,* **94,** 445 (1941).

[77] S. Moulton, T. T. Puck, and H. M. Lemon, *Science,* **97,** 51 (1943).

[78] H. G. du Buy, A. Hollaender, and M. D. Lackey, *U. S. Pub. Health Repts.,* Supplement No. **184** (1945). M. Frobisher, Jr., *The Fundamentals of Bacteriology.* 4th ed., Saunders. Philadelphia, 1949.

[79] R. Schneiter, J. E. Dunn, and B. H. Caminita, *U. S. Pub. Health Repts.,* **60,** 789 (1945).

The industrial hygiene methods for the collection of particulate matter of similar size are as effective for microorganisms as they are for other aerosols. The problem of evaluation, however, is complicated by the relatively small number of organisms in relation to other aerosols. These other aerosols and some gases collected simultaneously may inhibit or destroy the microorganisms when brought into intimate contact with them. Goetz[80] suggests collection by impingement of at least one cubic meter of air with dilute gelatin solution as the collecting medium. The gelatin solution is fortified or adjusted with such agents as acid or alkali buffers, antioxidants, or other protective chemicals to shield the microorganisms against locally prevailing conditions. The impinger fluid is filtered before and after use through molecular filters, and the retained microorganisms can be cultured "in situ." For more complete information on sampling and analytical methods see Volume III.

No satisfactory index of microorganism contamination of the air has been recognized, either in type or number. In the present state of development these problems are largely of a research nature, but doubtless within the next few years methods of evaluation and control of some forms of atmospheric contamination by microorganisms will have reached standardization levels.

PHYSICAL CHARACTERISTICS OF THE ENVIRONMENT

Instruments used by industrial hygienists for the appraisal of the environment and not previously considered in this chapter are discussed briefly here. These measuring devices and their proper use warrant detailed coverage beyond the scope of this chapter and are covered in Volume III.

Air flow. The Velometer is most widely used.

Noise. Most groups consider a readily portable sound-level meter and an octave-band analyzer to be the minimum equipment needed.

Ionizing radiation. Radiation survey meters are widely used for x-ray and gamma-radiation measurements. Scintillation meters to measure low levels of radioactivity have been and are being developed for many individual applications.

Illumination. The foot-candle meter has been the usual tool, but many will wish to supplement this with the brightness meter and the visual-index meter.

Ultraviolet radiation. Ultraviolet meters are available from lamp manufacturers.

Infrared radiation. Measuring methods include the black-bulb thermometer and radiometers.

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[80] A. Goetz, *Am. J. Pub. Health*, **43**, 150 (1953); A. Goetz, *J. Am. Water Works Assoc.*, **45**, 933 (1953)

CHAPTER VIII

Air Conditioning

KENNETH E. ROBINSON

Complete air conditioning includes the control of temperature, humidity, radiation, air movement or drafts, and cleanliness or purity of the air. The control of air cleanliness and air quality is generally a matter of ventilation and air cleaning. Since these subjects are covered in Chapters IX and X, only the thermal aspects of air conditioning are discussed here.

The installation of air-conditioning equipment in industrial plants is usually prompted by the desire or necessity to provide a controlled atmosphere for the product or operation, or to improve the environment for the employees. This chapter, devoted entirely to improving man's environment, is divided into two parts: (*1*) the effect of temperature and humidity on man and his well-being, and (*2*) the mechanics of providing suitable temperature and humidity for spaces occupied by man.

I. Physical and Physiological Principles*

Under ordinary circumstances of comfort and health, body temperature is kept approximately constant around its normal level of 98.6° F. through a balance between internal heat production (metabolism) and heat loss to the environment. The latter is made up of three components, according to the physical laws of heat transfer: radiation, convection, and evaporation. Thermal exchange between the human body and the environment[1] may be expressed in the following terms:

$$M = \pm S \pm E \pm R \pm C$$

where M = rate of metabolism; S = rate of storage, change in body heat content; E = rate of evaporative heat loss; R = rate of heat loss or gain by radiation; and C = rate of heat loss or gain by convection.

The rate of heat production, metabolism, is always positive in value. Since in the normal situations of comfort there is no change in body temperature, S is zero. It has a positive value when the body heats up and is negative with body cooling. R and C may be positive or negative, depending upon the direction of the skin-environment temperature difference. Evaporative exchange is always positive since a negative value (condensation) could only occur with a dew-point temperature higher than the surface temperature and this would be incompatible with life.

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* The section covering physical and physiological principles was written by Theodore F. Hatch.

[1] The concepts of partitional calorimetry on which this discussion is based were developed at the John B. Pierce Laboratory of Hygiene. Cf. C.-E. A. Winslow and L. P. Herrington, *Temperature and Human Life*. Princeton University Press, Princeton, N. J., 1949.

Heat exchange by radiation is proportional to the difference in the fourth powers of absolute radiant temperature of the body surface and of surrounding surfaces. As a first approximation, however, R may be expressed in terms of the simple temperature difference:

$$R = K_rA_r(t_s - t_w)$$

where $K_r = K(T_s^3 + T_s^2T_w + T_sT_w^2 + T_w^3) =$ approximate constant over modest ranges in T_s and T_w (K being the universal radiation constant, and T_s and T_w absolute radiant temperatures of body surface and surrounding surfaces, respectively); $A_r =$ effective radiation surface area of body (about 0.8 × actual surface area for sitting subject); and t_s and $t_w =$ radiant temperatures of body surface[2] and surrounding surfaces, respectively.

Heat exchange by convection depends upon the temperature difference between the body surface and surrounding air and upon the air velocity. Since "still" room air always has significant motion, the theoretical minimum exchange with free convection can be neglected and, practically, the convective exchange may be expressed as follows:

$$C = A\ K_c\sqrt{V}(t_s - t_a)$$

where $A =$ surface area of body in square feet; $K_c =$ coefficient of heat exchange by convection at unit velocity; $V =$ effective air velocity in feet per minute; and t_s and $t_a =$ temperatures of the body surface and air, respectively.

Evaporative heat loss is directly proportional to the amount of water evaporated from the body surface and respiratory tract. For a completely wetted surface, the evaporative rate depends upon the vapor pressure difference ($\mathrm{VP}_s - \mathrm{VP}_a$), where VP_s is the vapor pressure of water at skin temperature and VP_a is the partial pressure of water vapor in the air. At any given vapor pressure difference, evaporative rate increases with air velocity. For conditions of maximum evaporative cooling with the body surface completely wetted, the following expression has been derived:[3]

$$E_{\text{max.}} = AK_cV^{0.4}\ (\mathrm{VP}_s - \mathrm{VP}_a)$$

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[2] Human skin and ordinary clothing radiate like black bodies, the radiant temperature is, therefore, the actual surface temperature.

[3] N. Nelson, L. W. Eichna, S. M. Horvath, and T. F. Hatch, Thermal exchanges of man at high environmental temperatures, *Am. J. Physiol.*, **151,** 626 (1947).

where A = surface area of body in square feet; K_e = coefficient of heat exchange by evaporation at unit velocity; V = effective air velocity in feet per minute; and VP_s and VP_a = as given above.

According to these several equations, it is seen that thermal exchange between the human body and the environment depends upon four external *physical* factors: air temperature, radiant temperature, air velocity, and moisture content of the air. The several rates of exchange are modified, of course, by the kind and amount of clothing worn.

Heat exchange is also subject to delicate *physiological* control. The metabolic rate may be increased spontaneously by shivering to counteract body cooling; and, with continued cooling, the individual may engage in deliberate activity to increase heat production. In the heat, on the other hand, the experienced individual reduces his activity to keep M within acceptable limits. In cool environments, R and C are automatically reduced by a decrease in the rate of blood flow through the surface tissues, which thereby limits the amount of heat brought to the surface. The skin temperature is thus lowered but internal body heat is conserved. Conversely, in warm environments, blood flow to the surface is increased; this raises the skin temperature and R and C go up if positive, or decrease if negative. The greatest degree of physiological adjustment is provided through the mechanism of sweating and evaporation. With minimum activity in cool environments and under normal conditions of comfort, there is no need for active sweating and the only evaporative heat loss is the amount fixed by evaporation in the respiratory tract (proportional to volume rate of breathing and difference between the constant water vapor pressure in expired air and the partial vapor pressure in inhaled air) and by the rate of water transfer to the skin (insensible perspiration). Since insensible perspiration is limited in amount, heat loss by this avenue is ordinarily independent of the moisture content in the air. Evaporative heat loss under comfortable conditions amounts to 20 to 25 per cent of total output. With increasing heat load, metabolic or external, however, active sweating is initiated by the need for greater evaporative cooling to maintain thermal balance. Up to a certain point the desired balance is obtained and the sweating and evaporative rates will thus be automatically limited without regard to the moisture content of the air. A *maximum* evaporative cooling rate is reached with higher heat loads when sweat is produced in excess of the evaporative rate. At this point, the body becomes completely wetted and there can be no further increase in the cooling capacity, which is now limited by the air velocity and the vapor pressure difference, as outlined above.

Changes in human response at rest to different environmental temperatures are portrayed in Figure 1. Shown separately are: metabolic rate, the sum of heat exchanges by radiation and convection, heat loss by evaporation, and changes in body heat content (storage). Over a considerable range in environmental temperature no change occurs in metabolic rate. In environments up to 85° F., evaporative heat loss remains at a low level since M is adequately offset by R

and C and active sweating is not required. The sharp rise in heat escape by evaporation above this point reflects the onset of active sweating, which is called for because R and C no longer compensate for M. Below 80° F. storage is negative and the magnitude of heat depletion increases as the environment becomes progressively cooler. In contrast, heat storage does not increase significantly above zero in warm environments, owing to the beneficial effects of sweating and evaporation. For the resting man in light clothing, environmental temperatures of 80 to 85° F. are thus seen to constitute a zone of thermal neutrality where conditions are not too hot or too cold. The individual has to exert no special effort (such as shivering or sweating) to maintain thermal balance. In this zone, the loss of heat from the body is distributed approximately as follows: evaporation, 20 per cent; radiation, 40 per cent; convection, 40 per cent. For a little distance on either side of the neutral point there exists a zone of *vasomotor* regulation against heat and cold within which blood flow to the surface is automatically adjusted to promote heat flow from deep-body tissues or to conserve body heat. Below this region is the zone of *metabolic regulation* against cold. Above it lies the zone of *evaporative regulation* against heat, which, up to the point of 100 per cent wetted surface, is adequate to offset the heat load ($M + R + C$). In this zone, moisture content of the air is most important.

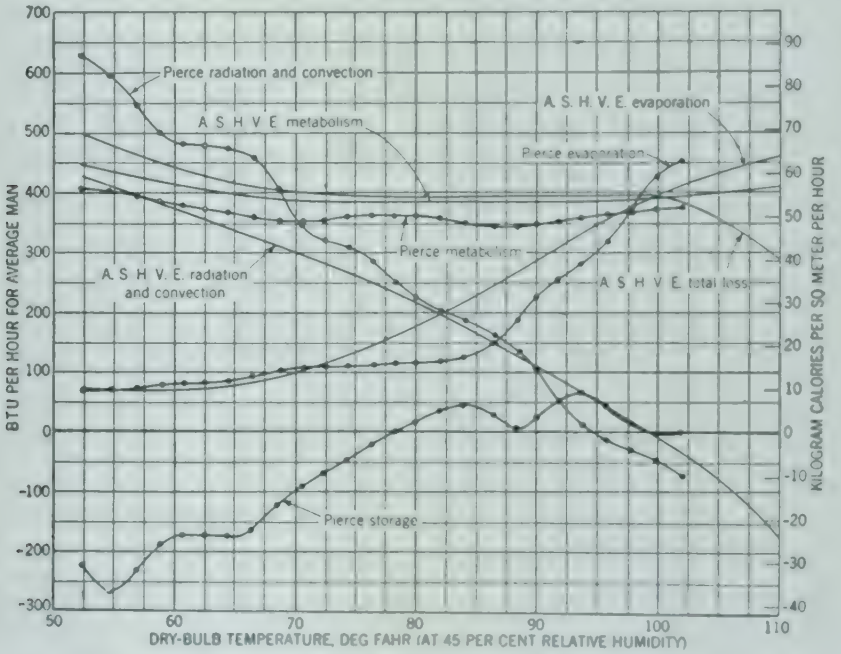

Figure 1. Relation between metabolism, storage, evaporation, radiation plus convection, and temperature for the clothed subject. (Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide 1957*, Chapter 6.)

A. EFFECTIVE TEMPERATURE SCALE AND COMFORT ZONE

The four environmental factors are independently variable and may be combined in many different ways to produce the same thermal effect on man.

Thus, an increase in air velocity will offset a rise in air temperature. Extreme radiant heat can be compensated by lowering the air temperature. A considerable elevation in air temperature can be tolerated if the relative humidity is low. Combinations of thermal conditions that induce the same thermal sensations are called thermoequivalent conditions. The Effective Temperature charts of the American Society of Heating and Air-Conditioning Engineers, shown in Figures 2, 3, and 4, give the combinations of equivalent conditions for clothed sedentary individuals and for workers stripped to the waist. According to the ET scale, any combinations of dry-bulb temperature, wet-bulb temperature, and air velocity

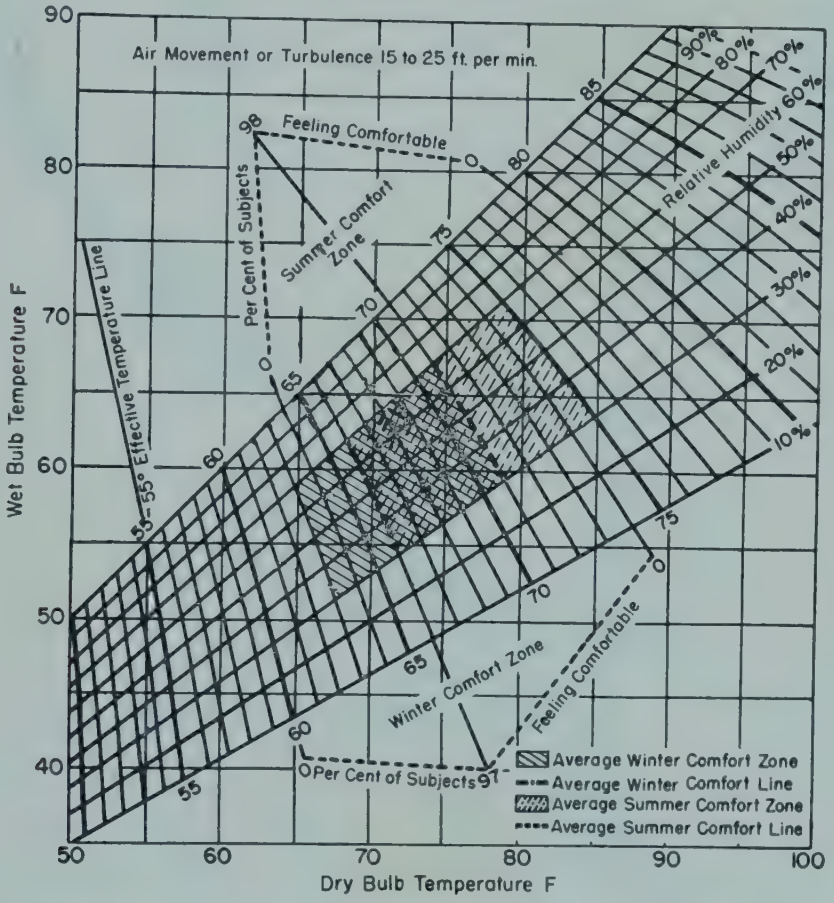

Figure 2. Comfort chart for still air. Both summer and winter comfort zones apply to the inhabitants of the United States only. Application of winter comfort line is further limited to rooms heated by central station systems of the convection type; the line does not apply to rooms heated by radiant methods. Application of summer comfort line is limited to homes, offices, and the like, where occupants become fully adapted to the artificial air conditions; the line does not apply to theaters, department stores, and the like, where the exposure is less than 3 hours. The optimum summer comfort line shown pertains to the northern portion of the United States and southern Canada, and elevations not in excess of 1000 feet above sea level. An increase of one degree in effective temperature should be made approximately per five degrees reduction in north latitude. (Reprinted by permission from *Transactions ASHVE,* Vol. 38, 1932, Report No. 933.)

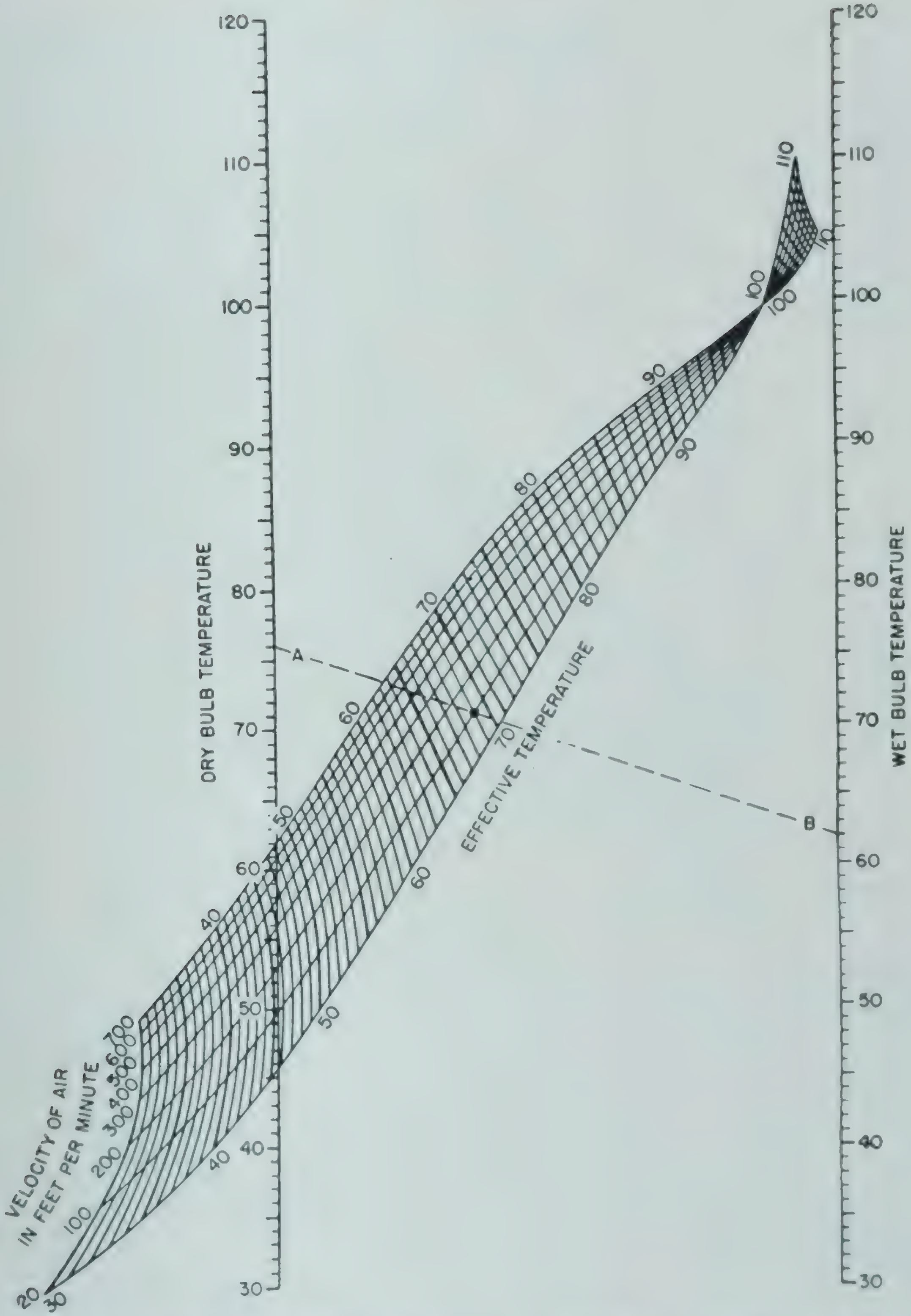

Figure 3. *Normal scale* of effective temperature applicable to inhabitants of the United States wearing customary clothing, at rest or doing light physical work, and in rooms heated by convection methods. (Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1957*, Chapter 6.)

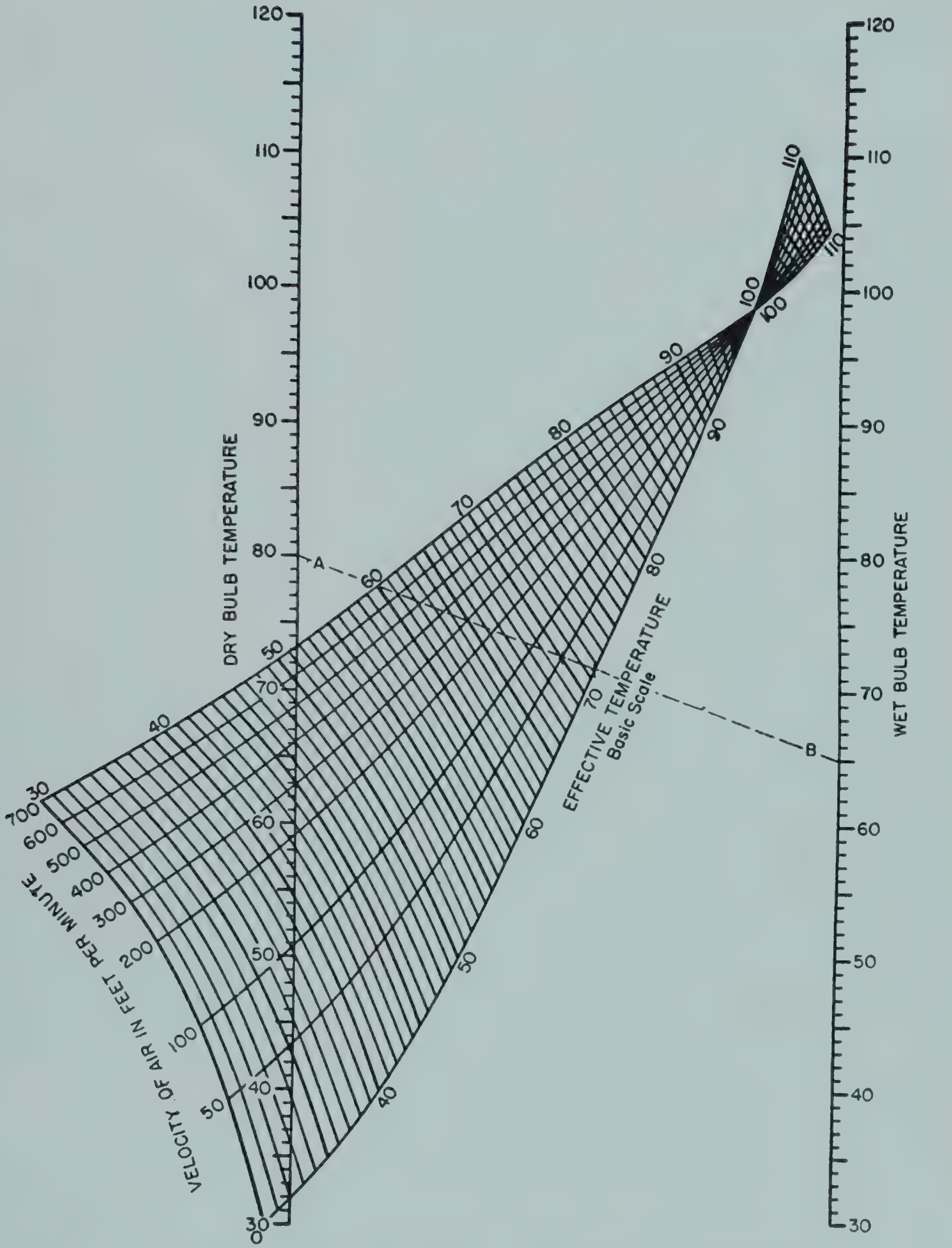

Figure 4. *Basic scale* of effective temperature applicable to men stripped to the waist, at rest or doing light physical work, and in rooms heated by convection methods. (Reprinted by permission from *Transactions ASHVE,* Vol. 38, 1932, Report No. 933.)

that give the same sensation of warmth as, say, 75° saturated still air, have an effective temperature of 75° F. Such combinations are easily read from the charts.

The effective temperature scales were derived by a "cut and try" procedure wherein test subjects moved from a control room into an adjacent test chamber and immediately recorded their thermal sensations. By repeated trials combinations of temperature, humidity, and air motion that, subjectively, felt like conditions in the control chamber were identified. Despite its limited subjective basis, laboratory and field experience with the ET scale has indicated that it is useful in defining the thermal comfort zone, and also that it correlates with objective measurements of physiological response to heat. In practice, the ET scale overemphasizes somewhat the influence of humidity in the comfort zone and tends to underestimate its effect in hot environments. It is, nonetheless, a valuable scale, which combines most successfully the several thermal factors of the environment into a single index value. The comfort zone outlined in Figure 4 may be used as the basis for specifying air-conditioning requirements for offices, light industry shops, and so forth. (For a discussion of the heat problem in the hot industries see Chapter XXI.) It is of interest to note the close agreement between the comfortable environmental temperature and the external conditions under which thermal neutrality is maintained, as suggested in Figure 1.

II. Environmental Control

Thermal comfort in the environment is the primary purpose of air conditioning. It has been shown that low temperatures reduce manual dexterity and increase accident frequency;[4] however, comfort, not accident prevention, has been the motivating force behind most heating installations (cf. also page 110).

Most industrial cooling installations have been decided upon because of an expected monetary return on the investment. Many articles have appeared in the literature pertaining to the savings that have been made by the installation of summer air conditioning and it is rapidly gaining acceptance.[5]

Inasmuch as man generates heat and is comfortable at room temperatures below body temperature, it should be remembered that the problem is always one of controlling the heat loss from the body, not of heating the man. To maintain an environment that will regulate the loss of heat from the body, it may be necessary to supply heat or humidity, to cool or dehumidify, or to vary the velocity of the air movement in the area. Many installations will require the consideration of more than one of these to arrive at a satisfactory condition.

A. ADDING HEAT TO A SPACE

The heat loss from a building is usually calculated in order to determine the amount of heat that must be added to maintain suitable inside temperatures.

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[4] E. E. Osborne and H. M. Vernon, *Ind. Fatigue Research Bd. (London). Rept. No.* **19**, H. M. Stationery Office, 1922.

[5] Is air conditioning worth the investment? *Heating, Piping Air Conditioning*, **26**, 119 (August 1954).

Because of their complexity these calculations will not be discussed here; they are available in the chapter on heating loads in the *Heating, Ventilating, Air Conditioning Guide* published annually by the American Society of Heating and Air-Conditioning Engineers.

Heat may be supplied to a space in two ways: by radiation or by convection.

1. Radiation

Thermal (heat) radiation is the transmission of energy by means of electromagnetic waves of very long wave length. Radiant energy of any wave length may, when absorbed, become thermal energy and result in an increase in the temperature of the absorbing body (see Chapter XXI). The most common method of supplying heat by radiation is with the ordinary radiator or some form of heated panel. These units may be heated by steam, hot water, or electricity and are found in a variety of shapes and sizes. The wall radiator is rapidly becoming extinct since it has a tendency to overheat anyone close to it while not supplying sufficient heat to people farther away.

Much has been written regarding radiant panel heating. The heat source for this system is usually buried in the floor or concealed behind the plaster of the ceiling or wall. It was thought that the use of low temperature radiation would result in comfort even though low air temperatures were maintained. Actually, in most cases, this has been just another way of heating the air. In garages, airplane hangars, and similar buildings where men work on the floor and large doors may be opened, greater comfort has resulted with heated floor panels. However, radiant panel heating has not always been satisfactory in factories because the lag in the controls has been too great to accommodate the rapid increase of temperature caused by a large sun load or the heat gain resulting from manufacturing processes.

When it is not possible or practical to heat the surrounding air at a reasonable cost, comfortable conditions have been provided by means of portable, semiportable, or fixed gas-fired radiant heaters. A receiving dock at a large unheated warehouse is a good example. Figure 5 illustrates an installation of fixed gas-fired radiant heaters used as the only heat source in a partially opened, uninsulated building.

2. Convection

Convective heat transfer is the transmission of heat by either natural or forced motion of a fluid (liquid or gas). In general, any heat source that air circulates around becomes a convector. This may be a wall radiator, a unit heater, a furnace, or coils; either mounted so that air moves over it because of the thermal lift created by the increase in the temperature of the air, or fitted with a mechanical fan to move the air over it. The concealed radiator or convector is seldom used in industry because it is difficult to locate, is bulky, and affects only a small area.

Unit heaters are very popular since they will provide large quantities of heat at a reasonable cost. They are usually mounted between the lower trusses and the roof, where space is easily available. Large units with coils and blowers or indirect fired furnaces are also used extensively and may likewise be mounted in the upper section of the plant. These units can be controlled automatically and, if properly sized and located, can also be used to bring in all or part outside air in winter and summer.

One of the difficulties with units located between the trusses is that when recirculation is used the warm air at the ceiling is drawn through the units, heated to a greater temperature, and discharged with a high velocity in an attempt to force it to the floor. This results in a hot blast over anyone in the immediate area while persons a few feet away may be cold. If operations in the plant generate any smoke and fumes that normally rise to the upper section of the building, these are also forced down toward the occupied area.

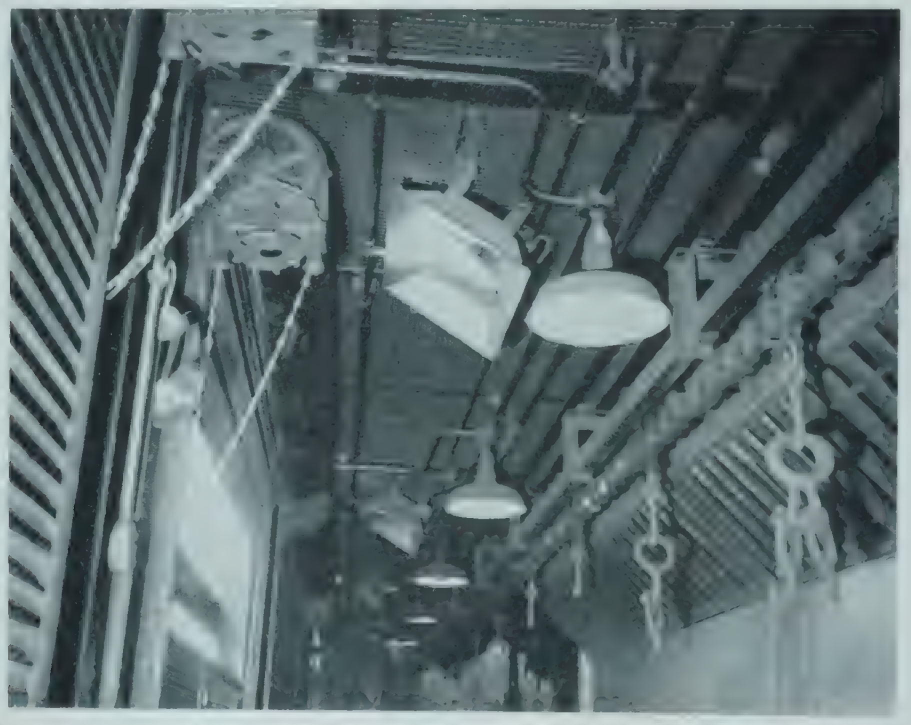

Figure 5. An application of radiant heat in a partially opened, uninsulated building. No other heat source is used.

Units used to supply heated outside air to replace that discharged by exhaust fans are usually installed in the same way and cause the same complaints from the occupants. In winter, it may be desirable to introduce air at less than room temperature to control the heat generated by the operation (see the discussion of make-up air on page 225).

3. Controls

Every method of supplying heat requires some form of automatic controls as part of the system. One method is to use an outdoor thermostat to control the valve that regulates the input to the heater. Such a system should include a thermostat within the building to maintain proper building temperatures when heat-producing operations are not running. Air-supply units that provide tempered air to the area should have both a room thermostat and a thermostat in the duct to assure proper temperature at all times. Otherwise the room control might be satisfied because of process heat and allow untempered air to be delivered.

The control for a steam system should have some method of assuring that sufficient steam will be supplied to the coil whenever the temperature of the outside air is below freezing, to heat the air supply to at least 40° F. Some systems are arranged so that the full steam capacity is provided whenever the outside temperature falls below 40° F., which prevents freezing but may cause overheating on mild days. This can be prevented if the valves on both the preheat and reheat coils and/or the face and bypass dampers are modulated by the control system. There are also special controls to place on the discharge side of the coil to shut off the unit if the air temperature drops below the control setting.

Many coils have been frozen because the condensate did not drain away properly. Contrary to the belief of many persons, there is no such thing as a freezeproof coil. A better name is a steam distributing coil, which will freeze if not properly protected.

B. REMOVING HEAT FROM A SPACE

This chapter concerns itself only with the problem of removing heat from a space (cooling) to provide suitable environment for employees, not for process cooling. It must be remembered that cooling is accomplished by removing heat from the room and that it is more difficult to remove than to add B.t.u.'s.[6]

The first approach to any cooling problem is to try to eliminate heat at its point of generation. Often this can be done by changing the operation; for example, by using induction heating rather than direct-fired furnaces for certain forging operations. The next step might well be that of isolation—the operation is removed to a separate building or a given section of the main building where it can be walled off and treated as a separate problem. On extremely large, hot operations, it is often more practical to supply small confined areas with cool air for the comfort of the operators than to try to cool the entire area.

Most of the above-mentioned approaches are fairly well understood. The biggest problem concerns large areas where some heat is generated throughout, such as large machine shops. When large numbers of people are employed, even the minimum approach is apt to be of sufficient magnitude to require the expenditure of considerable sums of money. Even on such operations there are some basic fundamentals that should be followed to evaluate the over-all problem. The entire area should be studied to locate the sources of heat generation. If the greatest amount of heat is coming through the roof from the sun load, consideration should be given to insulation of the roof deck, painting it with reflective paint, or perhaps spraying it with water to reduce the amount of heat transmitted to the room. If, on the other hand, most of the heat is generated by large amounts of electrical energy used throughout the area, little can be done to reduce this load at the source. In isolated cases some relief has been achieved by either locally ventilating the motors if they are large, or by adding small sections of duct work to air-cooled motors so that the heat is discharged above the heads of the employees. The use of man-cooling fans may lower the employees' effective temperature a little but does not remove heat from the space. Increasing the amount of air exhausted through the roof of the building is often disappointing, for replacement air flows in through open doors and windows and may follow along the ceiling and be exhausted with very little effect in the occupied zone. This is particularly true with the modern wide, flat type of building and experience has proved that surprisingly little relief is obtained from such installations.

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[6] Chapter on cooling load, *Heating, Ventilating, Air Conditioning Guide, 1955*. American Society of Heating and Air-Conditioning Engineers, New York, 1955.

Heat may be removed from the occupied space by introducing air at a lower temperature and then exhausting it after it has absorbed some of the heat in the area (see page 227). When the temperature of the air being introduced to the space is too high to give satisfactory relief it may be lowered by (*1*) evaporative cooling or (*2*) a chilled coil system.

1. Evaporative Cooling

In evaporative cooling the air is passed through sprays of water or some porous material wetted with water. The condition of the air leaving the cooler depends on the efficiency of the unit, the wet- and dry-bulb temperatures of the entering air, and the temperature of the water. Although the evaporative cooler is usually thought of as adding a good deal of moisture to the air, this occurs only when the temperature of the spray water leaving the cooler is lower than the dry-bulb temperature and higher than the dew point of the entering air. Cooling also takes place at the same time. If the spray water leaving the cooler is at the dew-point temperature of the entering air, sensible cooling only results; and if lower than the dew-point temperature of the entering air, both cooling and dehumidifying occur.[7]

Unfortunately, engineers have usually discussed evaporative cooling only in connection with comfort plotted at or near the 71° ET line, which has resulted in the belief that it should not be considered in many parts of the country. There are few places where it cannot be used, and even though true comfort may not be reached, at least an improvement is made and tolerable working conditions can be maintained. High air volumes and air movement must be incorporated in the design, however.[8]

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[7] H. M. Hendrickson, *Heating and Ventilating*, **50**, 91 (July, 1953).

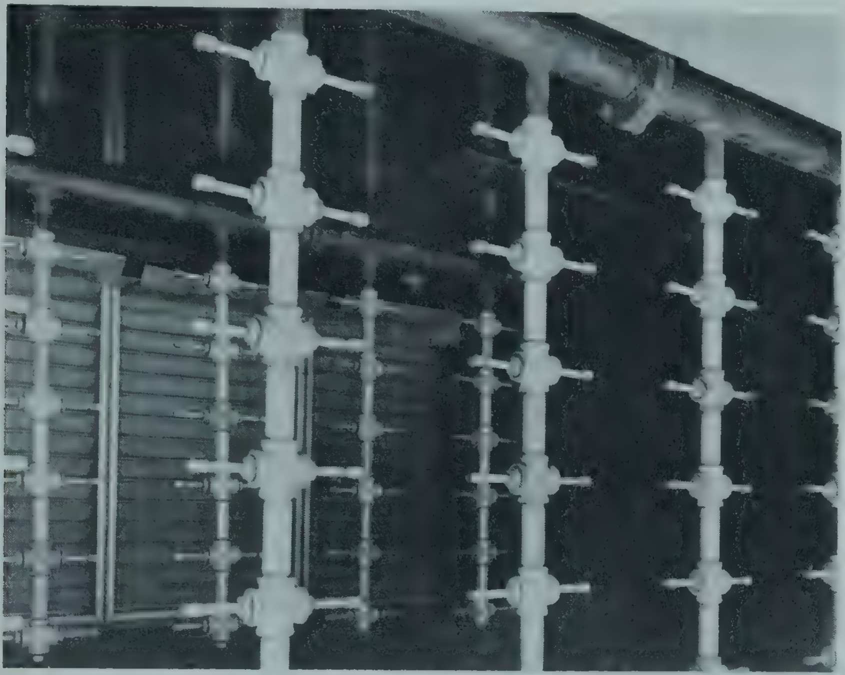

Figure 6. Evaporative cooler showing two banks of nozzles and eliminators. (Courtesy American Blower Corp., Detroit, Mich.)

2. Chilled Coil System

In a chilled coil system air is passed over coils containing some medium whose temperature is sufficiently below that of the air to result in satisfactory cooling. These systems are usually of one of the following types:

a. Water-Cooled Coil. In this system, which is the simplest, water directly from the supply is circulated through the coil while air from the conditioned space is passed over the coil to remove heat and moisture. As a general rule water must enter the coil at not more than 52° F. and is wasted after leaving the coil unless it is used for process work.

b. Cooled Water System. When water is not available in sufficient quantities or at satisfactory temperatures, it may be artificially cooled and recirculated. This system is often used when the coolant must be piped long distances and a variety of loads must be overcome. Usually the heat is removed from the water by mechanical refrigeration, but in some intermittent operations, such as church cooling, it is removed by the melting of ice.

c. Refrigerated Coils. As the name implies, the coils are cooled by the direct vaporization and expansion of the liquid refrigerant. This method is widely used in small units as well as large central systems.

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[8] W. T. Smith, *Heating, Piping, Air Conditioning,* **27,** 141 (August, 1955).

C. HUMIDIFICATION

There are two general methods of humidifying air spaces: (*1*) the indirect method, which involves the use of an air washer, and (*2*) direct methods, in which the water is introduced directly into the space being humidified.

The indirect system is usually preferred where ventilation is also required because it is only necessary to supply air through the sprays of a washer and the needed moisture is thus added. The heat necessary to vaporize the moisture comes either from the heat stored in the water or from transformation of sensible to latent heat in the air.

Direct humidification is usually more desirable wherever high relative humidities must be maintained in a space where air movement or cooling is not required. In some industrial applications where high humidity and a low ventilation load must be maintained, a combination of the two systems may be used. There are many methods employed to atomize the water for direct humidification.

Occasionally steam is released into a room to add humidity, or water is dropped on a hot plate to be vaporized and so furnish the humidity. Care must be taken that odors of an undesirable nature do not result with the first method and, with the second, that the minerals in the water are not deposited throughout the room. More detailed information on these and other types of humidifiers is available.[9]

D. DEHUMIDIFICATION

Dehumidification of (or reduction of the water vapor in) air or other gas is usually obtained by (*1*) cooling the air stream below the dew point or (*2*) passing the air over or through some form of sorbent. Cooling the air stream below the dew point is accomplished by passing the air through cold water sprays or over coils containing either chilled water or a refrigerant. This causes some of the water vapor to condense and be removed from the air stream. It also cools the air stream, which may then have to be reheated or mixed with warmer air before it can be introduced to the occupied space.

The second method uses either an absorbent or an adsorbent to remove the excess moisture. Calcium chloride is one absorbent material frequently used; it may be either solid or liquid (solution). Other liquid absorbents are solutions of such chemicals as lithium chloride, lithium bromide, and ethylene glycol. The liquid absorbent is reactivated by passing it through an evaporative condenser where the moisture is evaporated by heat and rejected to the outside atmosphere. Adsorbent materials, which may be silica jel, activated charcoal, or others, have the ability to adsorb moisture from the air without changing either physically or chemically. The adsorbent is usually reactivated by being heated to drive off the adsorbed moisture.

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[9] *Heating, Ventilating, Air Conditioning Guide.* American Society of Heating and Air-Conditioning Engineers, New York (published annually).

While air temperature is reduced when dehumidification is obtained by cooling the air below the dew point, it must be remembered that there is a heat gain in the air discharged from these sorbent units, which may be objectionable.

E. AIR DISTRIBUTION

The distribution of an air-handling system is often the most neglected and yet perhaps the most important part of the installation. The problem of air distribution may be divided into three parts: (*1*) supplying air above room temperature (heating), (*2*) supplying make-up air to replace that being exhausted, and (*3*) supplying air below room temperature (cooling). Cooling may be further subdivided into (*a*) air motion only, (*b*) evaporative cooling, and (*c*) mechanical cooling.

1. Supplying Heat

Heat is usually supplied only on the basis of adding sufficient B.t.u.'s to the building to offset the heat loss. As has been mentioned previously in this chapter, it should be supplied to provide a suitable temperature for the inhabitants of the building. When the problem is approached with this thought in mind, it is often found that it may be desirable to introduce air to the space either above or slightly below the desirable room temperature. If all of the air that passes through the heater is coming from the building and being recirculated, its temperature, of course, will be either equal to or above the temperature found in the room. This is the simplest unit to operate and the easiest from which to distribute air. Contrary to common installation practice, it is not desirable to introduce high-velocity, heated air into the occupied space. The air should be introduced in such a way that the velocity does not exceed 50 feet per minute, and usually not more than 25. This can be accomplished either by using diffusion-type grilles, which entrain room air with the air being discharged, thereby equalizing the temperature and reducing the velocity, or by discharging the air horizontally through grilles with horizontal deflectors so that the air flows above the heads of the people and the only air motion on them is that caused by the air entrainment.

2. Make-up Air

Air supplied to replace that being exhausted is usually termed make-up air. However, air may be introduced to the room during winter months to reduce temperatures that have been elevated by the heat from production. In some cases the quantity of make-up air is so great that the temperature of the building is controlled by the heat supplied to this large volume of air. If this is the case

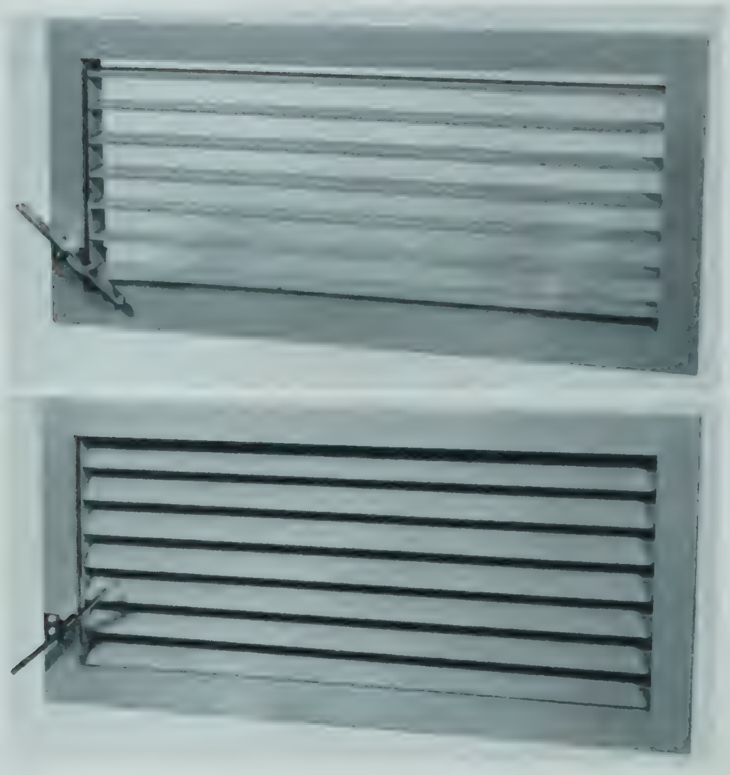

Figure 7. Grill for air-supply system showing adjustment of blades so air can be discharged horizontally (upper) or 45° downward (lower). (Courtesy Hart and Cooley Manufacturing Co., Holland, Mich.)

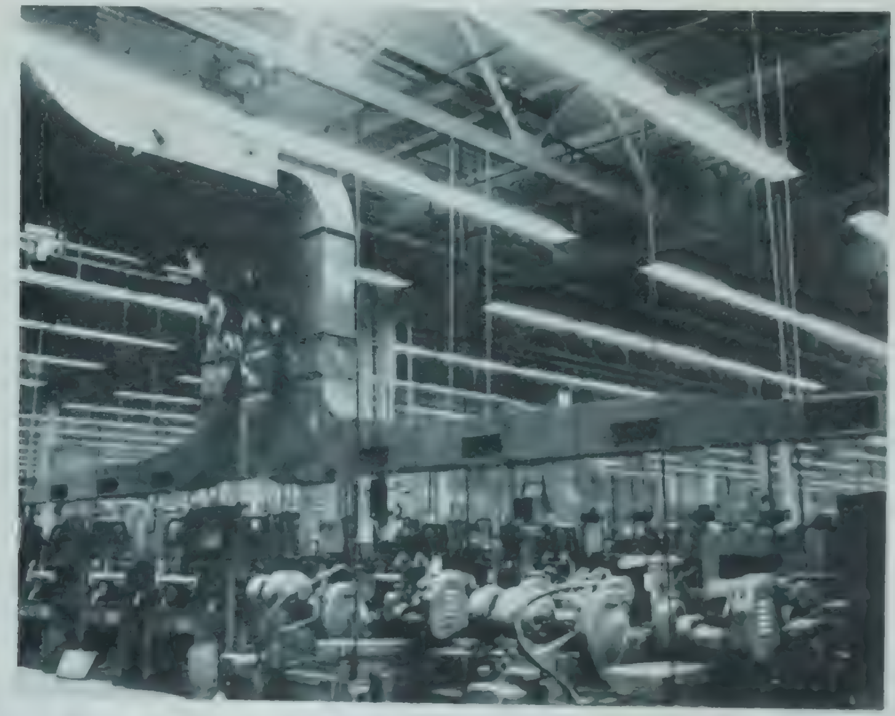

Figure 8. Air-supply system to deliver air into occupied zone.

and the temperature of the air is always to be above room temperature, the suggestions set forth above under supplying heat can be followed. However, if it is desirable to bring the air in at less than room temperature to offset the heat gain from processes, greater care must be exercised to see that proper diffusion and air entrainment are maintained. If any smoke or fumes are generated in the area, it becomes more important to introduce this air as close to the actual occupied zone and as near the floor as is practical. In most installations the registers have been between 8 and 10 feet from the floor.

3. Removing Heat

a. Air Motion Only. When air is introduced into a space during warm weather for the purpose of reducing the effective temperature, the air motion is very important. The reduction of effective temperature is accomplished by the increased rate of heat loss by evaporation and convection from the body due to this air motion. Under such circumstances there does not seem to be agreement as to what velocities may be used. The effective temperature chart shows the results of motion up to 700 feet per minute; however, many of the hot industries use air velocities of 3000 feet per minute and more (see Chapter XXI).

It has been found to be most desirable and effective to supply the air as near to the people as is practical. In this way the coolest air available is moved across them and at the same time the minimum amount of heat, smoke, and fumes is entrained in the air supply before it comes in contact with the occupants. Another advantage of supplying the air in this manner is that if the outside air temperature is reduced either by local storms or by the normal drop of temperature in the evening, the people inside immediately get the benefit. This is not true if air is introduced at the ceiling of the building. In a number of plants air is introduced at the floor, either from tunnels or from duct work brought down to the floor level. This allows the air to be distributed around the people with an absolute minimum of smoke or heat entrainment. The selection of grilles for such an installation is of particular importance. They should be easily adjustable, preferably of the type that may be adjusted by the room occupants so that the air may be introduced directly on them when the building is hot and near them when outside temperatures are too cool for direct contact. It may be that the adjustment will be made two or three times a day depending on circumstances. A line of industrial grilles has been especially designed by one manufacturer to meet the above conditions. There are no dampers on these grilles to allow the employees to shut off the air supply, but they may be obtained with adjustable vertical bars if desired.

b. Evaporative Cooling. The same rules apply when supplying air from an evaporative cooler as when only air motion is desired. In fact, part of the time the water supply may be interrupted and the unit used only to supply air. The one thing that must be remembered with both of these methods is that large volumes of air at high velocities should be provided to give the occupants the benefit of the maximum air flow.[10]

c. Mechanical Cooling. When mechanical cooling is used to cool a space the air-distribution system should be such that the maximum amount of diffusion is provided at the discharge registers. This causes the cold air supplied to be thoroughly mixed with the room air for maximum cooling of the space with minimum objectionable drafts being felt by the occupants. The lower the ceiling, the more important is the diffusion. There are many companies manufacturing special grilles for this purpose, most of which have a high entrainment ratio, which makes them quite suitable. Where low ceilings are involved systems in which a plenum chamber is provided above the ceiling proper so that the air enters the room through small perforations in the ceiling are increasingly popular. When properly installed these work very satisfactorily.

In plants with high ceilings the effectiveness and economy of the system can be improved by properly delivering the air close to the occupied space, as where air motion only is used for removing heat (page 227).

In general, it must be remembered that at all times the main objective is to cool the occupant. It cannot be determined whether air motion or diffusion is needed from the outlet until the method of cooling the man is decided. Every effort should be made to design and install a system that will give the maximum benefit throughout the entire year.

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[10] K. E. Robinson, *Plant Engineering,* **11,** 86 (February, 1957).

CHAPTER IX

Air Cleaning

W. N. WITHERIDGE

This chapter deals with the principles of air cleaning and the problems of selecting effective equipment for controlling the quality of air in the industrial environment.

I. Applications of Air Cleaning

Two groups of applications are considered: (*1*) cleaning of air to make it acceptable for supply to indoor areas, and (*2*) cleaning of waste air or gas before discharge to the outer atmosphere, to avoid air pollution. Certain methods of air cleaning occupy a borderline position, suitable for both air conditioning and air-pollution control.

A. AIR-CONDITIONING APPLICATIONS

Air-cleaning equipment may be included in air-conditioning or ventilating systems for practically any confined space, whether stationary or moving: buildings, underground shelters,[1] protective enclosures (such as "iron lungs"), elevators, automobiles, buses, railroad cars, ships, submarines, and aircraft.

In these applications, air must be delivered in respirable condition, which means the proper oxygen content as well as a minimum of impurities. In addition, it may be necessary to produce air of sufficiently high quality to protect furnishings, manufacturing equipment, and products, such as biologicals, optical goods, or precision instruments.

Indoor air may be recirculated to conserve energy, or contaminated outdoor air may be treated to make it acceptable for indoor use.

Recirculation from Air Cleaners

The advantages and necessities of recirculating air in commercial and residential air conditioning are well established. The trend toward more complete control of the atmosphere in manufacturing establishments for comfort, health, safety, product quality control, and equipment preservation has forced the designer to consider recirculation where never before attempted.

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[1] W. Viessman, *Heating, Piping, Air Conditioning,* **26,** 122–127 (November, 1954), 84–88 (December, 1954).

Recirculation is feasible and safe with exhaust systems on some kinds of processes, in combination with effective air-cleaning devices. The demand in many communities to reduce the industrial contaminants discharged outdoors has made it apparent that consideration should be given to recirculation in some situations to eliminate air pollution as well as save the cost of heating or cooling air used for ventilation.

B. AIR-POLLUTION CONTROL APPLICATIONS

Industrial communities are demanding better atmospheric conditions, and good progress is being made in the development of more effective air-cleaning equipment to meet lower permissible concentrations of contaminants. The satisfaction of present air-pollution regulations may not assure the desired results for more than a brief period of time. Under this situation, it is wise to select the kind of air-cleaning equipment that can be operated or modified later to meet greater restrictions.

While the industrial hygienist is concerned primarily with protection of human life and health, he should not overlook the economics of air cleaning. To encourage full co-operation of those who finance the installations, extravagant methods of control should be avoided.

Further discussion of air-pollution problems will be found in Chapter XIII. Equipment for removing contaminants from effluent air or gas is reviewed in the present chapter.

Conservation or Waste Prevention

Air may be "cleaned" to conserve energy or valuable materials. Although it is not often possible to realize enough savings to offset the cost of air treatment, it is good business to approach each application with conservation in mind. New markets for materials or new developments in technology may so alter the economic balance that a formerly prohibitive plan of conservation may become a practical venture.

When air or gas cleaning is contemplated because of a need to minimize air pollution, consideration should be given to the possibility of completely eliminating the discharge or loss from the process. This is material conservation or waste prevention at its best, and the most certain method of preventing air pollution.

II. Air Quality Requirements

Air-conditioning applications of cleaning equipment may be rated in general as "light duty," while equipment for air-pollution control tends to be "heavy duty." This distinction is based on the amount of material to be removed from the air. However, so far as air quality is concerned, cleaning of air for indoor use generally demands the highest possible degree of separation leading to the lowest concentration of contaminant at the discharge of the cleaning equipment. Cleaning of air or gas discharged outdoors as a waste from industrial processes generally does not require as high a percentage of removal as specified for air discharged indoors.

A. PERMISSIBLE CONCENTRATIONS FOR INDOOR DISCHARGE

Opinions about the relation that should exist between the concentration of a contaminant in the air-cleaner effluent and the permissible concentration to protect human health differ widely. Some contend that air should be discharged substantially cleaner than the ambient concentration, even when dilution is inevitable; others are satisfied with discharge at room concentration; while still others feel that discharge can be permitted at a concentration above that of the room or space, to an extent based upon rate of ventilation or air change. Consequently, the air-cleaning engineer should determine not only the permissible concentration for the contaminant in question, but also the acceptable relation between this concentration and that occurring in the air-cleaner effluent.

Permissible concentrations of many substances are given in the list issued annually by the American Conference of Governmental Industrial Hygienists. This list is also published in the annually revised *Heating, Ventilating, Air Conditioning Guide* of the American Society of Heating and Air-Conditioning Engineers. Values having the widest acceptance at the time of this publication are given in Chapter VI.

B. WEIGHT, COUNT, AND VISUAL RATINGS

Separators or cleaners that depend chiefly upon the ability of particles to leave an air stream because of their inertia or momentum generally will exhibit favorable performance on a contaminant weight basis, and disappointing performance on a particle count basis. They will also be relatively ineffective in changing the visual character of contaminated air, inasmuch as light reflectance or obscurance is caused chiefly by particles below one micron in size. To avoid confusion or misinterpretation of the data, particle size information should accompany all ratings of performance based on particle weight, count, or visibility.

C. BLACK-WHITE DISTINCTION FOR AIR-BORNE MATTER

Indoor discharge from an air cleaner is subject also to a critical appraisal that involves what might be called the "black-white distinction." It has long been observed that air-filtering devices installed for the purpose of minimizing the blackening effect of fine particle deposition around the edges of air-distribution devices are best rated in terms of a blackness test. This test recognizes the discoloration nuisance of predominantly carbonaceous matter in metropolitan atmospheres. At the same time it reveals separation ability for particles chiefly in the submicron range.

It is important to keep in mind that submicron white solid particles may not have the same nuisance potential as the equivalent sizes of black or dark-colored particles. Although particle size distribution is an essential consideration for intelligent interpretation of performance data, there are numerous cases where size information should be accompanied by color. Air-borne solid matter does not have the same blackening power at all points on its size-distribution curve. Generally, where color distinction is important, the relatively great surface area of the smaller particles will make them a greater nuisance.

D. REMOVAL OF AIR-BORNE ORGANISMS

A good correlation exists between the number of microorganisms in air and the concentration of dust particles. It is concluded, therefore, that many organisms or bacteria are attached to air-borne dust particles, and consequently will be removed from the air by dust-separating devices. Organisms carried by droplets, such as are produced by coughing or sneezing, likewise can be removed by air cleaners capable of separating fog or mist particles.[2]

An important precaution should be observed in the case of air washers. If means are not taken to inhibit or prevent the growth of organisms in recirculating water tanks, bacteria or virus may be returned to the occupied spaces by entrainment of mist in the air stream. If mist or fog evaporates while in transit to the space under treatment, microorganisms may be left air-borne and so contribute to a gradually rising concentration in the course of air recirculation.

Air filters treated with adhesives may accumulate a luxuriant growth if the viscous material does not contain germicidal or inhibiting agents. A serious odor nuisance can result from bacterial decomposition of organic matter accumulated on filters.

III. Properties of Aerodispersions

The classification and description of various forms of matter that may be carried by an air stream into a cleaning device appear in Chapter VI and need not be repeated here.

Many properties of a gas and its impurities should be considered in planning an effective cleaning installation. Some are evident; others are easily overlooked. A comprehensive review of these properties is not possible here, but a check list of characteristics is offered to aid in selecting the ones that are apt to be significant in a particular application. Brief comments will be made about a few properties that are important in the design and application of most air-cleaning systems.

A. PROPERTIES OF THE CARRIER GAS

These physical properties or conditions of the air or gas should be reviewed before designing or selecting a system for removing impurities:

1. Quantity or rate of flow, preferably by weight.

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[2] H. M. Decker, F. A. Geile, H. E. Moorman, and C. A. Glick, *Heating, Piping, Air Conditioning*, **23**, 125–129 (October, 1951); H. M. Decker, J. B. Harstad, F. J. Piper, and M. E. Wilson, *Heating, Piping, Air Conditioning*, **26**, 155–158 (May, 1954).

2. Temperature: actual at inlet, and desired at outlet.
3. Pressure: at inlet, and allowable change.
4. Density.
5. Viscosity.

Air Temperature and Pressure. Of all the properties of the carrier gas that confront the designer of cleaning equipment, temperature requires the greatest attention. It affects the phase distribution of suspended matter, chemical activity, molecular diffusivity, gas viscosity and density, durability of construction materials, and size of equipment. Both pressure and temperature may determine the phase of air-borne matter, along with chemical nature. For most applications though, pressure changes are negligible compared with temperature changes, and therefore temperature is the controlling condition.

Pressure is considered in designing the structure to provide the necessary strength and prevent leakage into the surrounding atmosphere, but it usually has negligible effect upon the cleaning processes. However, research workers are careful to assess the importance of pressure in diffusion processes, and where viscosity or density may influence the migration of particles through the fluid.

B. PROPERTIES OF AIR CONTAMINANTS

Many properties of matter carried by the air or gas should be considered before designing or selecting equipment for its removal. It is true, of course, that for any one application, the list of significant properties may contain only a few of the following items:

1. Water distribution: solid, liquid, and vapor phase; presence of water in suspended solids (water is treated as a foreign constituent whenever the carrier fluid is not water vapor or steam).
2. Composition of solids, liquids, and gases.
3. Concentration of each constituent.
4. Particle size distribution, or screen analysis.
5. Unusual shape characteristics of solid particles.
6. Density of solid or liquid particles.
7. Porosity of solid particles.
8. Condensation temperature, or dew point, of vapors.
9. Sublimation temperature, or freezing point, of solids or semisolids.
10. Diffusivity of gaseous or submicron constituents.
11. Solubility in water or other collecting liquids.
12. Volatility or vapor pressure.
13. Hygroscopic or hydrophobic tendency.
14. Adhesive or cohesive nature of particles.
15. Presence of magnetic particles.
16. Electrical characteristics.
17. Hardness, abrasiveness, erosiveness.
18. Corroding or etching potential.

19. Flammability, explosibility.

20. Physiologic effects: toxicity, irritation, odor.

Concentration of Contaminants. The magnitude of dust concentrations or "loadings" encountered in air or gas cleaning may be exhibited on a simplified scale:

100 g./m.^{3}	pneumatic conveying
10 g./m.^{3}	heavy loadings from processes
1 g./m.^{3}	moderate loadings
0.1 g./m.^{3}	light loadings; essentially clear effluents in daylight
10 mg./m.^{3}	dusty workroom air
1 mg./m.^{3}	acceptable concentration of "nuisance" dusts
0.1 mg./m.^{3}	country atmosphere

There is evidence that the concentration of solids in the range applying to pneumatic conveying has an influence on the effectiveness of cyclone separation. There appears to be an improvement of separation at the high concentrations somewhat in the nature of a large-particle "stampede," or a "carry along" of small particles.

In the case of electric precipitation, a high concentration of particles interferes with the charging process and with the retention of charges by particles until they reach the collecting surfaces. Accordingly, high concentrations affect this separation process adversely.

Increase in the concentration or partial pressure of a gaseous constituent tends to increase the removal percentage in scrubbing towers. Assuming a fairly low equilibrium concentration at the gas-liquid interface, an increased concentration of gas in the air stream gives an increased "driving force," causing the gas to pass into the scrubbing liquid. However, if the liquid approaches saturation with the gas, or the driving force is reduced, the percentage of gas transmitted across the interface into the liquid declines.

Concentration of a gas or vapor in the air affects the retentivity of adsorbents, and thus the percentage of the contaminant they will separate. For fresh or regenerated adsorbent, the separation ratio may be essentially independent of vapor concentration in the air stream. As the adsorbent approaches saturation with the gas being separated, its retentivity for that substance gradually drops to zero.

Particle Size. A statement of the separating ability of an air cleaner without reference to the size of solid or liquid particles removed is as indefinite as specifying the air-flow capacity of a blower without stating the resistance it will overcome. In other words, a percentage figure for the effectiveness of a dust separator is practically meaningless when standing alone. Performance specifications should contain a qualifying phrase of the following form when solid or liquid particles are involved: ". . . based on the fraction below —— microns"; ". . . based on the fraction above —— microns"; or ". . . based on the fraction between —— and —— microns."

In some cases, where exceptional performance is expected, it is important to specify not only the particle-size distribution of air-borne matter but also the method of size analysis. There is no universal method of measuring particle size that can be used for the rating of air- or gas-cleaning equipment.

Figure 1 is Johnstone's[3] adaptation of data on characteristics of air-borne matter and capabilities of various separating devices on the scale of particle size.

"Screen-size" particles, generally considered those over 44 μ, are easy to separate in the simplest types of equipment, including gravitational separators.

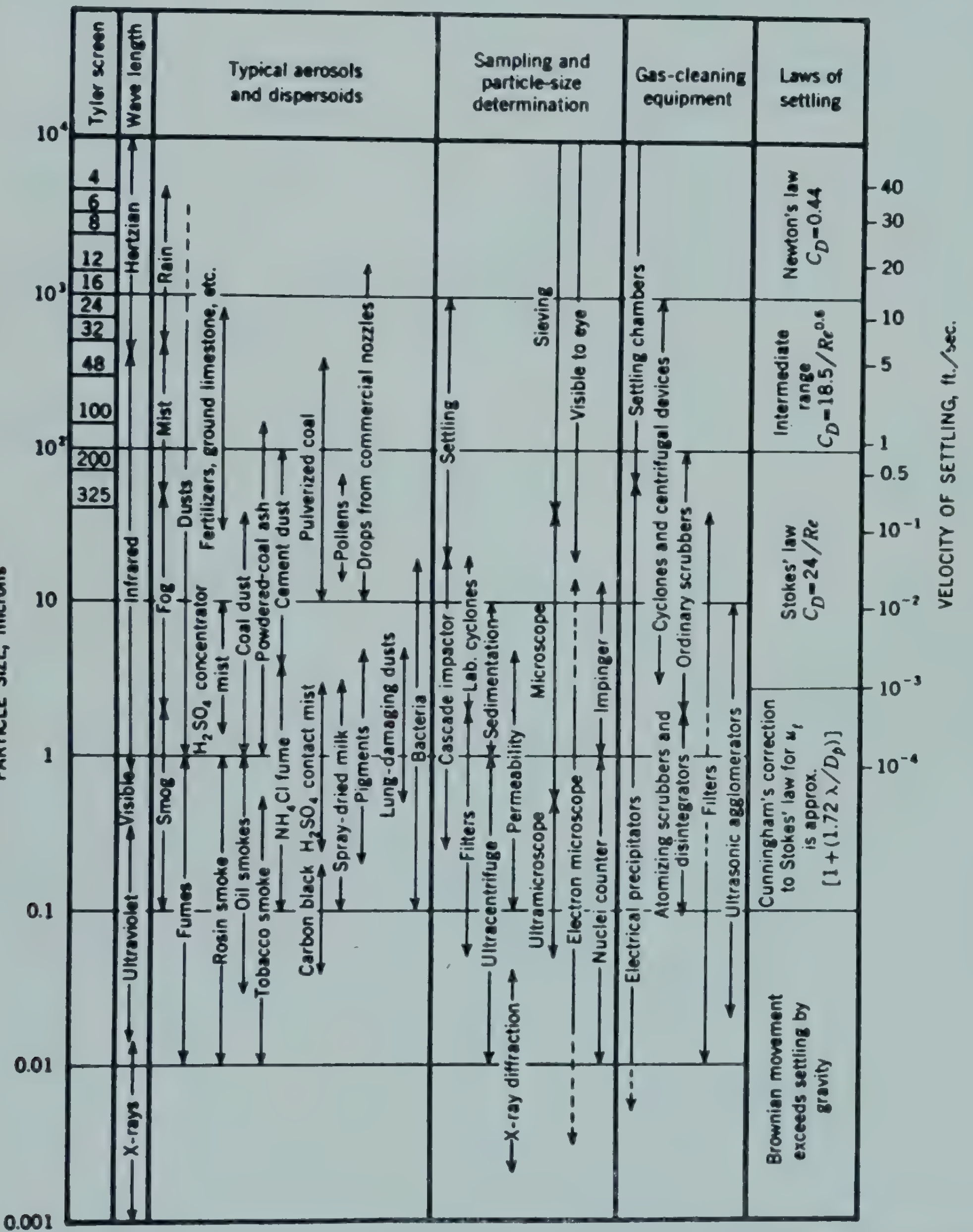

Figure 1. Characteristics of air-borne matter and capabilities of air-cleaning devices related to particle size. Settling velocities are for spheres of density 1 in air at 70° F. (From Johnstone.[3])

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[3] H. F. Johnstone, Gas cleaning and purification, *Encyclopedia of Chemical Technology,* Vol. VII. Interscience Encyclopedia, New York, 1951, pp. 83–106.

"Subscreen sizes" require well-engineered equipment to remove them from air or gas, and the difficulty of separation increases as particle size decreases. "Submicron" particles, which include many varieties of solid fumes, demand the most effective separating equipment, exceedingly well engineered and incorporating features that often result in high-cost installations.

The determination of particle-size distribution is necessary for correct application of air-cleaning equipment. This subject is treated in Chapter VII and also in Volume III.

Terminal Settling Velocity. A highly useful concept in the air-cleaning field is the *terminal velocity* or constant settling velocity reached by a particle falling under the influence of gravity. A particle less than about 1000 μ in size will fall with a velocity at which the resistance to its motion offered by the fluid balances the gravitational force tending to accelerate its motion toward the earth.

Foley[4] presented convincing reasons for expressing particle size, mass, and shape by means of terminal velocity when required to predict the performance of inertial separators against solid particles. In fact, it was noted that terminal velocity already has been adopted in some European countries for specifying the performance of gas-cleaning systems.

The behavior of particles in a moving gas can be measured directly in such devices as the Roller Air Elutriator, described in Volume III.

Particle Shape. Although terminal settling velocity integrates particle shape with size, density, and porosity, it does not describe completely the behavior of particles that deviate strongly from the spherical, in the direction either of fibers or of discs or flakes. It is well known that a solid object of irregular shape tends to present its largest cross section perpendicular to its direction of movement through a fluid. Accordingly, the orientation of a particle during its approach to a filter medium can influence the probability of its capture. The best common example is the ease with which lint can be separated in home air conditioners by relatively open filter media.

Fibers may acquire a spinning or rotating tendency, while discs or flakes may move with an oscillating or sideslipping action. Particles of less definite shape will exhibit combinations of spin and sideslip, and these complex movements may be helpful in the process of filtration. It is suggested, therefore, that terminal velocity specifications be supplemented with information on particle shape when the performances of filters and inertial devices are compared in research or product-development studies.

Fractionation of Air-borne Materials. An estimate of the character of air-borne matter can be made by examining the materials charged into or produced by a process. Care is necessary, however, to account for any tendency of the process to fractionate such materials, resulting in a distribution of size, phase, or chemical species, as suspended in the air, that is different from that in the bulk form.

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[4] R. B. Foley, *Trans. Am. Soc. Mech. Engrs.*, **69**, 101–108 (1947).

The use of long ducts between a process and the air-treating equipment is certain to change the nature of heterogeneous suspensions. Gravitation, condensation, adhesion, flocculation, frictional charging, and even leakage, all contribute to the gradual fractionation of the suspended matter.

It is reasonable to assume that fractionation will occur in one way or another, and any assertion to the contrary should be supported by convincing evidence. The true character of contaminated air entering a cleaning system should be obtained by a series of samples taken directly from the air stream at that point.

IV. Specification of Performance

A statement of the performance of air- or gas-cleaning equipment on a given application should include most or all of the following factors:

1. Amount of material retained or discharged (to be discussed in this section).
2. Size distribution of particles retained or discharged.
3. Air-cleaning capacity in cubic feet per minute.
4. Air velocity at a specified location.
5. Resistance or pressure drop through the equipment.
6. Space requirement in cubic feet or in floor area.
7. Storage or holding capacity for contaminant.
8. Life under specified conditions of service.

If the object of air cleaning is the recovery of suspended materials, it is important to know the percentage or amount of material collected or retained in the equipment. On the other hand, in air-pollution control and air conditioning, the percentage of material collected is only incidental information. If the object is to produce air of better quality for supply to occupied spaces, or of lower nuisance character before discharge outdoors, then performance should be specified in terms of the amount of contaminant in the outgoing air stream.

Measurement of the degree of cleaning usually is done with sampling devices operating as minature separating and collecting systems with the highest possible effectiveness. It is therefore apparent that performance of an air- or gas-cleaning system is based on the performance of the sampling device used in determining the nature and amount of contaminants at the inlet and outlet of the cleaning system. Accordingly, the method of testing should be specified in a statement of performance, and if it is not standard in the field, with known capability, the testing device itself should be described well enough to be duplicated. (A thorough discussion of air- and gas-sampling equipment is presented in Volume III.)

A. EFFICIENCY OR EFFECTIVENESS

It should be understood that the word "efficiency," in the field of air or gas cleaning, does not refer to the proportion of energy used effectively in the cleaning process. Instead, it is used almost exclusively to indicate the proportion of matter removed from the air stream, without regard to the amount of power required.

Complete removal of a certain constituent would be rated as "100 per cent efficient" cleaning, no matter how extravagant might be the consumption of energy. Recognizing the need for a better expression for this measure of performance, some engineers have used the terms *per cent collection*, *per cent removal*, *per cent recovery*, *per cent retention*, *arrestance*, among others. In this discussion, "effectiveness" is the preferred term, and the rating of performance on a 100-point scale will be stated directly as "per cent" or "percentage."

The proportion of material escaping or passing through the separator is sometimes identified as *per cent passage* or *per cent penetration.*

B. SEPARATION DEGREE

In view of the increasing necessity of high-quality air-cleaning equipment operating in the range of 95 to 100 per cent separation, it is the opinion of this writer that a logarithmic scale of rating is in order. A mass transmission degree scale has been devised for use in the correlation of data on performance of separation processes.[5]

Separation degree is defined here as the base-10 logarithm of the ratio of incoming concentration to outgoing concentration:

$$\text{Separation degree} = \log \frac{\text{incoming concentration}}{\text{outgoing concentration}}$$

Separation degree may also be determined from per cent effectiveness, E:

$$\text{Separation degree} = \log \frac{100}{100 - E}$$

One-degree separation is defined as 90 per cent reduction in the concentration of air-borne matter from inlet to outlet of the air-cleaning device, or an outgoing concentration $1/10$ that of the incoming concentration. The relation between separation degree and per cent effectiveness may be indicated by a brief tabulation. The symbol ⊕ has been adopted for separation degree.

Effectiveness, in per cent	Separation, degrees	Concentration, in/out
50	0.3 ⊕	2/1
90	1 ⊕	10/1
95	1.3 ⊕	20/1
99	2 ⊕	100/1
99.9	3 ⊕	1000/1
99.99	4 ⊕	10,000/1
99.999	5 ⊕	100,000/1

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[5] W. N. Witheridge, *Fundamental Concepts in Gas Cleaning* (Ph.D. thesis, University of Michigan). University Microfilms, Ann Arbor, Michigan, 1951.

The advantages of a logarithmic scale of rating equipment performance are chiefly mathematical and graphical. Correlation studies may be reported and analyzed with convenient straight lines on logarithmic graphs, using separation degree as one of the scales. It is particularly helpful for reports of the performance of multistage separating mechanisms, such as highly effective multiple-layer filters, or sequential systems, represented by the cascade impactor. For example, if we assume that air is filtered through a multiple-layer filter having identical construction in each layer, or stage, and that the air contains submicron particles of absolutely uniform size removed to the extent of 50 per cent in each layer of the filter, then it would take 10 layers to produce, theoretically, a total percentage separation of 99.9, which is 3 degrees of separation: 50 per cent = 0.3 degree per layer; 10 times 0.3 = 3.0 degrees total; 3 degrees = 99.9 per cent separation.

C. REFERENT DIFFICULTY OF SEPARATION

Table 1 indicates the effectiveness of various air-cleaning mechanisms against contaminants arranged roughly according to particle size. For this purpose a referent difficulty of separation has been selected, and the value chosen is *one degree,* or 90 per cent separation. This is the ability of a cleaner to deposit

TABLE 1

Effectiveness of Air Cleaners

Type of cleaner	Contaminants	Particle size, in microns, 90 per cent removed (one degree separation[5])
Gravity settling chambers	Dust, mist	50–100
Baffle chambers	Dust, mist	20–50
Low G cyclones	Dust, mist	20–50
High G centrifugals	Dust, mist	5–10
Rotary centrifugals, dry	Dust	5–20
Inertial louvered cones	Dust	10–20
Spray washers	Dust, mist, pollen, vapors, gases	5–20
Centrifugal scrubbers	Dust, mist, pollen, vapors, gases	2–10
Packed tower scrubbers	Mist, fog, vapor, gas	1–5
Fog or venturi scrubbers	Dust, fog, fume, gas	0.1–2
Intensive rotary scrubbers	Dust, fume, vapor, gas	0.1–1
Impingement filters, viscous	Dust, mist, pollen	5–10
Deep-bed fibrous filters	Dust, fume, spores, bacteria	0.5–2
Cloth arrestors, filters	Dust, fume, spores, bacteria	0.2–1
"Absolute" filters	Dust, fume, spores, bacteria	0.01–0.1
Electric precipitators	Dust, fume, fog, spores, bacteria	0.01–10
Thermal precipitators	Dust, fume, fog, spores, bacteria	0.01–10
Active carbon filters	Vapor, gas, odor	Molecular

and retain 90 per cent of the specified contaminant carried into the equipment by the air. Separation in the range from 90 to 100 per cent encounters a range of difficulty from 1 to infinity, which is correctly indicated on the degree scale here advanced. There are occasions when the engineer must make this situation clear to the client who desires an effluent concentration that is an extremely small fraction of the inlet concentration.

It is of interest here that the *Decontamination Factor* (DF) of the Atomic Energy Commission is occasionally used as an index of air-cleaning equipment performance. It is the same dimensionless number as our *separation degree*.

V. Classification of Cleaning Processes

Air-cleaning equipment is generally classified according to its predominating features. The resulting simplified grouping of devices gives only an approximate indication of the forces and mechanisms operating in the cleaning process. The simplified classification used here is the following: (*1*) preparation (conditioning, activation, injection); (*2*) settling chambers (gravitational separators); (*3*) inertial separators (cyclones, centrifugal separators); (*4*) filters (dry or adhesive media); (*5*) electric precipitators; (*6*) liquid systems (washers or scrubbers); (7) combination systems.

TABLE 2

Classification of Air-Cleaning Forces and Mechanisms

- Preparation actions or processes
  - Conditioning of the air
    - Cooling and condensation
    - Humidification (especially for electric precipitators)
  - Injection of treating materials
    - Gas or vapor injection
    - Liquid injection (spray, mist, or fog)
    - Solid particle injection (flocculation; sorption)
  - Activation of particles
    - Sonic agglomeration
    - Particle charging (electric; frictional)
- Separation forces or mechanisms
  - Precipitation (gas flow and deflection unnecessary)
    - Gravitational field (settling chambers)
    - Electrostatic field
    - Thermal field (chiefly sampling devices)
    - Diffusional field (concentration gradient)
  - Deflection (differential momentum or inertia)
    - Linear flow (impingement; impaction)
    - Helical flow (stationary or rotary centrifugal)
  - Filtration (gas-flow channel subdivision; deflection; diffusion)
    - Rigid medium (screen, fabric, porous solid)
    - Loose solid medium (packed bed or column)
    - Liquid medium (bubble column)

In view of the informative nature of a classification or arrangement of subject matter in any field, it is desirable also to examine the nature of cleaning processes, forces, or mechanisms by means of a classification that more nearly agrees with fundamental concepts (see Table 2).

The classification suggested here features the segregation of processes of *preparation* from those of *separation*. This is done for analytical reasons, and does not imply either the possibility or desirability, in practice, of sharply dividing the operations of conditioning an aerodispersion from those of separating matter from the gas. The distinction between preparation and separation is made to ensure that requirements of both functions are fully considered in relation to each other and are met by the designer so far as practicable. Many failures can be traced to inadequate provisions for treating, conditioning, agitating, cooling, flocculating, charging, or otherwise preparing the air and its contaminants for cleaning or separating processes.

Three subdivisions of preparation are shown in the classification; each characterizes a general approach, comprising many techniques now in use: (*1*) conditioning the gas, (*2*) injection of additives, and (*3*) activation of suspensoids.

The processes of separating matter from a gas have been arranged in three groups according to the manner of handling the gas: (*1*) The category of *deflection* represents the view that separation is the result of differentially curved paths for the carrier gas and the separated particle, causing differential inertia or momentum. (*2*) The category of *precipitation,* or nondeflection, does not depend upon a curvilinear path to accomplish separation; it considers the path of the carrier gas to be linear; separation is the result of forces generated externally, rather than by deflection of the gas. (*3*) The category of *filtration* represents the mechanical provisions for adjustment of channel size and configuration to activate or take advantage of particle energies. It recognizes that effective filtration calls for the best balance between the several processes that occur simultaneously, ranging between centrifugal migration and molecular diffusion.

It is well to note that separation and preparation functions are simultaneous to a certain extent. A good example is the so-called single-stage electric precipitator, in which the particles are charged and precipitated in the same unit, although in a fractional way along the air-flow path. It is true, however, that many advantages accrue from the practice of arranging the installation in separate units, each of which has a specialized share of the entire job of air cleaning.

With a desire to improve the performance of an air-cleaning system, it is wise to analyze all units or stages of a combination system from the viewpoint of their potentialities as preparation devices, in addition to their essential functions as separation devices. The sequence of stages can be arranged so that each will accomplish an objective of preparation in the interest of better separation in subsequent stages.

VI. Preparation of Aerodispersions

When gravitational or inertial methods of separation are anticipated, it may be helpful or even necessary to devise preliminary treatment of the gas with the object of causing particles to join or coalesce to larger sizes. The process is described as *flocculation*, *agglomeration*, or *coagulation*. Those who are familiar with water treatment will recognize the analogy.

Flocculation. Flocculation proceeds to a certain extent as a result of molecular activity in the gas, which produces random agitation of particles known as *Brownian movement*. The smaller the particles, the more vigorous their movement, approaching that of the molecules themselves for colloidal sizes. Where space is available, advantage can be taken of the spontaneous agglomeration resulting from Brownian-movement collisions by permitting a sufficient retention time in the equipment to "age" the suspension, so that particles will fall in clusters or colonies to the base of the settling chamber.

Flocculation can be accelerated by increasing the opportunity for particle collision. This may be done by: (*1*) injecting fine particles, such as a water fog; (*2*) increasing vibratory energy by raising gas temperature; (*3*) increasing gas turbulence by mechanical arrangements, or by filtration; and (*4*) increasing relative velocities between particles by subjecting the gas to sound energy.

Sonic Agglomeration. Sonic or ultrasonic agglomeration makes use of frequencies from about 2,000 to 50,000 cycles per second, and energy intensities of the order of 100 watts per square foot (about 150 decibels). It is applied, preferably, where particles are below 10 μ in size and at concentrations of 1 grain per cubic foot or higher. Frequencies in the audible range from 2,000 to 20,000 cycles per second require special precautions to prevent a noise nuisance. At the present time sonic agglomeration is not widely used for preparing aerodispersions for the separation stages of air cleaning.

VII. Gravitational Separators

Settling chambers are presumed to have been the earliest means of recovering dust from process gases. Ducts or flues were enlarged to reduce the gas velocity and permit a fraction of the dust to settle and be removed at intervals by hand. Horizontal ducts several hundred feet long were constructed early in the century for the recovery of metallurgical materials and for air-pollution abatement. The largest gravitational separator ever built was installed at the smelter of the Anaconda Copper Mining Company in Great Falls, Montana, in 1909. This system handled nearly one million cubic feet of gas per minute through a dust chamber 370 feet long connected by a 1330-foot flue to a chimney 500 feet high.

The tremendous servicing problem, as well as space requirement, made these systems obsolete soon after the development of a practical Cottrell electric precipitator. However, they are still found in limited use where space is no problem, and improved methods of collecting the deposit are available.

Similar in principle to these long settling flues is the system now in limited use for process dust exhaust mains. Air velocity is reduced as the branch ducts enter a large main, allowing the coarse particles to fall out before the air enters a secondary stage of cleaning. The main duct is so shaped that a conveyor can be installed at its base for continuous removal of the settled dust and chips.

The low gas velocity required for gravitational separators results in low pressure drop, making possible their application to natural-draft exhausts from equipment such as kilns or furnaces. Gravitational separators are generally rated as impractical for subscreen sizes, meaning 325 mesh (44 μ) or smaller.

One of the simplest forms of gravity settling chambers is a large vertical cylinder, or "silo," into which are discharged the effluents from numerous dust-exhaust systems. The top of this chamber is provided with an opening area determined by the gas velocity to convey the maximum size of particle to be allowed to escape from the interior. While this is inherently a bulky device, its simplicity has brought it favor in several cases where ample space was available adjacent to the building containing the dust-collecting and -transporting machinery.

Industrial processes, such as the blast furnace and melting cupola,[6] characterized by the passage of gases at high velocity through granular or fine-grained substances, are capable of discharging particles several thousand microns in size, according to the gas velocity and the physical properties of the materials. In these cases, removal of a large portion of matter from the carrier gas is accomplished simply by moderate deceleration of the gas to permit the largest particles to drop by gravity into a primary separator of reasonable size.

Gravitational Separator Design. The following features of design are basic to effective use of gravitation in removing solid or liquid particles from air:

1. Highest possible air outlet; discharge from the top of the chamber is preferred.
2. Lowest possible position of air inlet, or lowest position of the air-flow path in relation to the discharge position; this suggests air inlet near the base of the chamber, but deflection of air downward to the base, and then upward to the air outlet, is even better.
3. Lowest possible air outflow velocity; also may be specified as the longest possible retention time; this controls the minimum size of particle that can be retained.
4. Largest possible horizontal collecting surface; extension of the surface along the axis of air flow works together with low air velocity to achieve long retention period; maximum settling area extends the period of accumulation or reduces the frequency of cleaning the chamber, which is especially important if this work is not mechanized to be continuous.

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[6] *Control of Emissions from Metal Melting Operations.* American Foundrymen's Society, Des Plaines, Ill., 1955; W. N. Witheridge, *Heating and Ventilating,* **46,** 69–84 (December, 1949).

VIII. Inertial Separators

The separating force on a particle can be magnified over that of gravity by causing the air to change its direction of flow, thereby creating centrifugal force. Nearly all types of air-cleaning equipment make use of centrifugal force to some extent because it is difficult to conduct air through a system of cleaning units without subjecting it to numerous changes of direction.

Inertial separators have been designed with virtually every possible geometric arrangement of air-deflection elements. The designer tries to exert the greatest possible centrifugal force on the suspended particles while expending the smallest amount of energy on the air stream.

The centrifugal separator is a device that can make the best possible use of particle inertia or momentum to cause the air and the suspended particle to travel separate paths. Deflection of air creates a spectrum of particle trajectories, and the designer takes advantage of this spectrum to skim off the coarser fraction down to a size required by the specified percentage of separation.

Particles of extremely small mass have so little momentum that they tend to follow the stream lines of a gas around any stationary object in its path, or any object passing through it. Nevertheless, impingement devices of the type used for air sampling can be operated at sufficiently high velocities to separate a high percentage of submicron particles (cascade impactor, for example). The smaller the particle to be removed from air by centrifugal force, the greater must be the energy expended on the particle in a specified unit of time. Therefore, as particle size decreases, a point is reached where inertial separation becomes impractical, compared with methods that emphasize diffusional forces.

Separation Factor. By using the centrifugal force produced by deflecting a high-velocity air stream, the separation effect on a particle can be increased to several thousand times that of gravity. The separating force is proportional to particle mass and the square of tangential velocity and inversely proportional to the radius of curvature of the path it is forced to travel.

The *separation factor* is the ratio of centrifugal force to the force of gravity and is presented graphically in Figure 2.[7] It is determined from the expression:

$$S = V^2/rg$$

where S is the separation factor referred to gravity, V is the tangential air velocity, r is the radius of curvature of air-flow path, and g is the acceleration of gravity. Separation factors based on inner vortex velocities in a cyclone will be several times greater than indicated in Figure 2 for tangential velocities in the outer vortex.

Pressure Drop in Centrifugal Devices. Pressure drop in centrifugal mechanisms is usually expressed in terms of velocity pressure at the inlet to the equipment (see Chapter X). The range of pressure drop encountered in most cyclone separators is from 2 to 20 inlet-velocity heads, depending on geometry and vortex intensity. In the absence of pressure-loss data for the selected design, it is reasonable to expect a pressure drop equivalent to 5 velocity heads, as a rule of thumb. Thus, an inlet velocity of 4000 feet per minute, which represents a velocity head close to 1 inch of water, may give a pressure drop through a cyclone on the order of 5 inches, water gage.

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[7] J. L. Alden, *Design of Industrial Exhaust Systems*, 2nd ed., Industrial Press, New York, 1948.

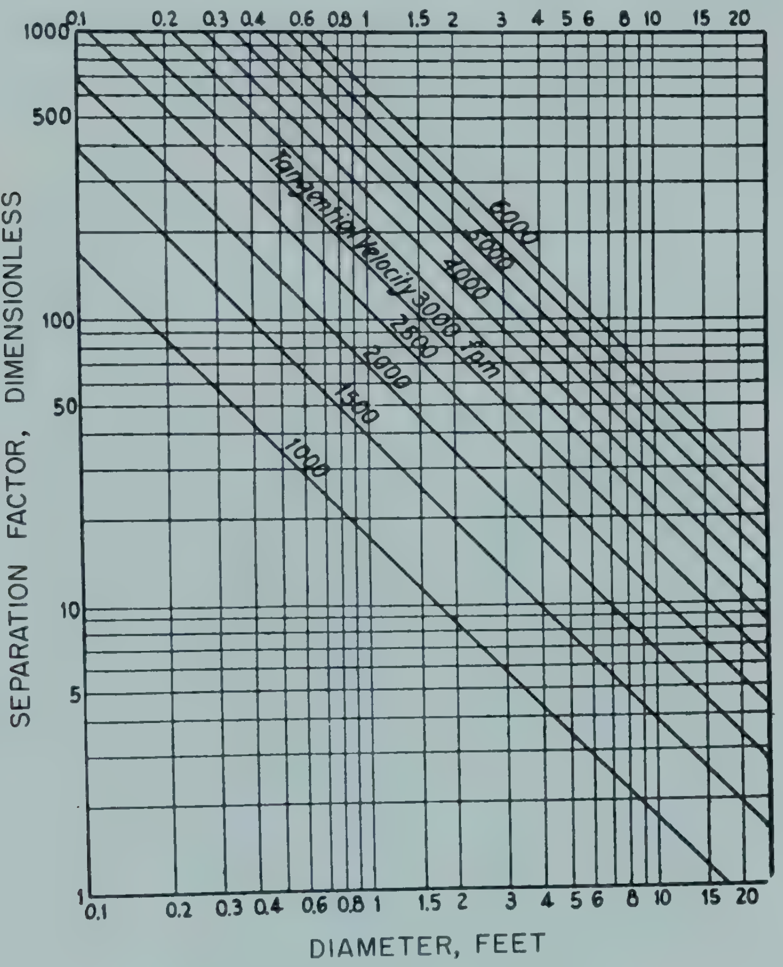

Figure 2. Separation factors for centrifugal devices. (From Alden.[7])

Data on pressure drop for particular designs of inertial separators should be obtained from the manufacturers, or by direct measurement under operating conditions. Computations with an empirical equation probably will be no more accurate than the above noted rule of thumb, unless the equation was developed as a calibration of the exact design selected.

A. BAFFLE OR IMPACT SEPARATORS

Baffles or deflectors, in a settling chamber or enclosure through which the air or gas is driven, cause the coarser particles to be thrown out of the stream by centrifugal force and impact. The number of obstructions placed in the air stream can be increased to the extent of creating an impingement filter capable of removing smaller particles. A serious difficulty with baffle separators is the turbulence created in the flowing air or gas. This tends to resuspend a portion of the separated dust, especially when operated dry.

B. LOUVERED OR SLOTTED SEPARATORS

The size of baffles may be reduced to the order of perforations in sheet materials, resulting in a separating device that might be termed a "centrifugal filter." The louvered-cone separator is a commercial adaptation of this principle, arranged to concentrate a portion of the air-borne solids in a fraction of the air stream, which is passed on to a secondary centrifugal separator (Figure 3).

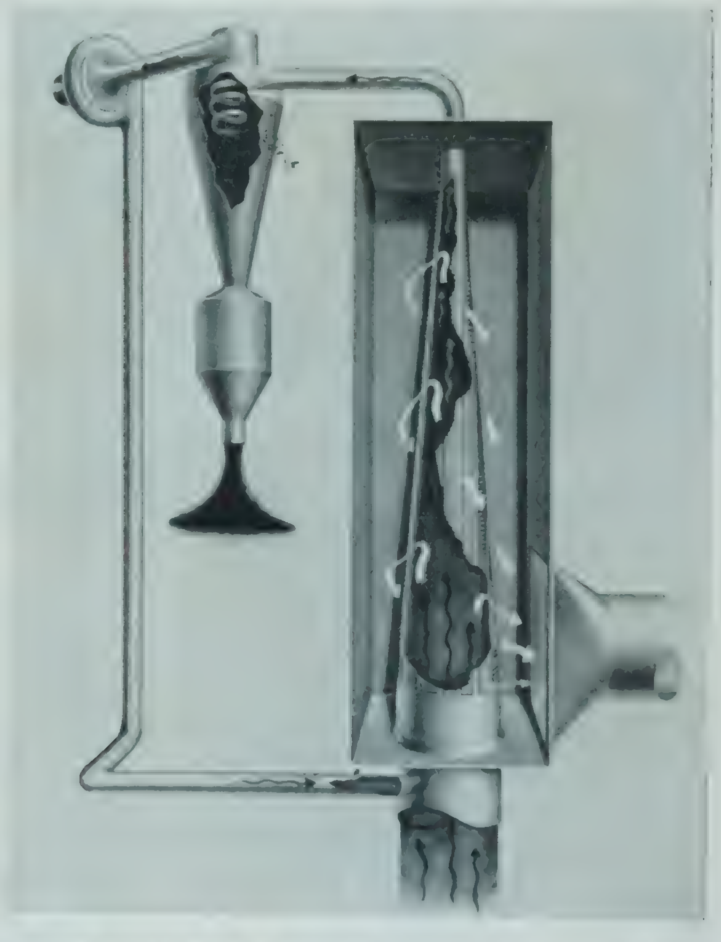

Figure 3. Louvered-cone separator with secondary cyclone. (Courtesy Aerodyne Division, The Green Fuel Economizer Co., Beacon, N. Y.)

C. CYCLONE SEPARATORS

Air enters a *cyclone separator* tangentially at one or more points near the periphery, developing a spiral, helical, or vortical flow pattern (Figure 4). Solid or liquid particles are separated from the air by centrifugal force, which increases in intensity as the air velocity increases toward the section of smallest diameter. The internal velocity in a cyclone may reach many times that of the inlet or outlet velocities, and a separator in which a powerful vortex is developed is sometimes called a *vortex separator*.

It is generally understood that large-diameter cyclones are effective against the relatively coarse particles encountered in industrial-process exhaust systems, and accordingly they have come to be known as primary separators in a wide variety of combination systems of air cleaning. As the diameter of the cylinder or cone is reduced, to make possible the separation of smaller particles, the air-flow capacity at reasonable pressure drop is also reduced. Therefore, multiple-tube equipment becomes necessary when large volumes of air are treated with small-diameter cyclones. An example of this arrangement is shown in Figure 5.

D. ROTARY CENTRIFUGAL SEPARATORS

A rotating element, similar to the impeller in a centrifugal fan, will throw suspended solid or liquid particles to the periphery of its housing or "scroll." Several commercial separators make use of this action and provide a compact unit combining the functions of a centrifugal fan and an inertial separator (Figure 6). A liquid spray at the inlet improves the ability of rotary separators to retain solid particles, and converts them to *centrifugal scrubbers* (Figure 7).

The rotating member must be maintained in good dynamic balance to minimize the vibration that tends to keep particles in suspension as air passes through the equipment. Air turbulence inherent in this design interferes with separation of fine particles, and it is common practice to follow rotary separators with other cleaning mechanisms. Abrasive wear tends to be high in such equipment, and consideration should be given to means for keeping it at a minimum.

IX. Filters

Filtration is defined here as the process of passing a fluid through a chamber more or less filled with obstructions to present a large area of contact or impact between the fluid and the filter "medium." This concept covers a multitude of designs, and leads to the use of the term *filter* as an alternate to cleaner or separator.

Filter media are porous materials of uniform or variable density, either shallow or deep, in which air-borne particles can be stopped by one or more actions, such as screening, impingement, static attraction, or diffusion. When filters with variable density or porosity are used, the direction of air flow is usually from the coarse to the fine sections of the filter medium. This helps to

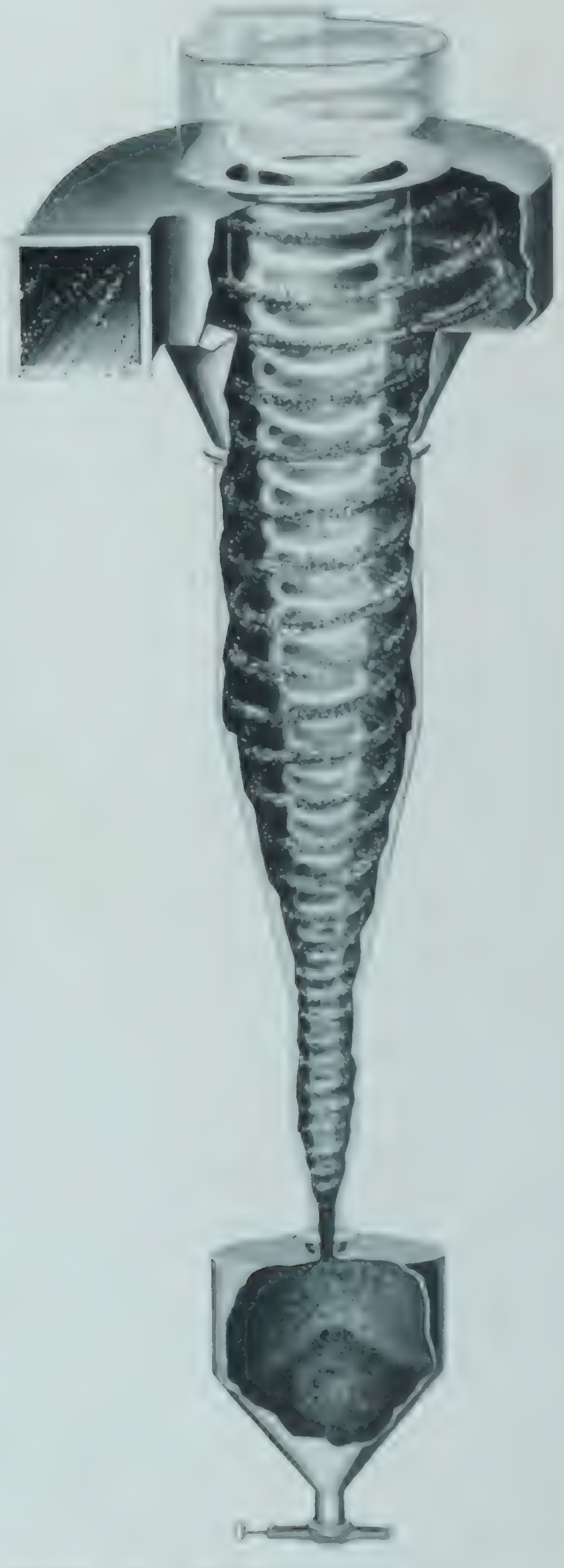

Figure 4. Centrifugal separator with tangential outlet. (Courtesy American Blower Corp., Detroit.)

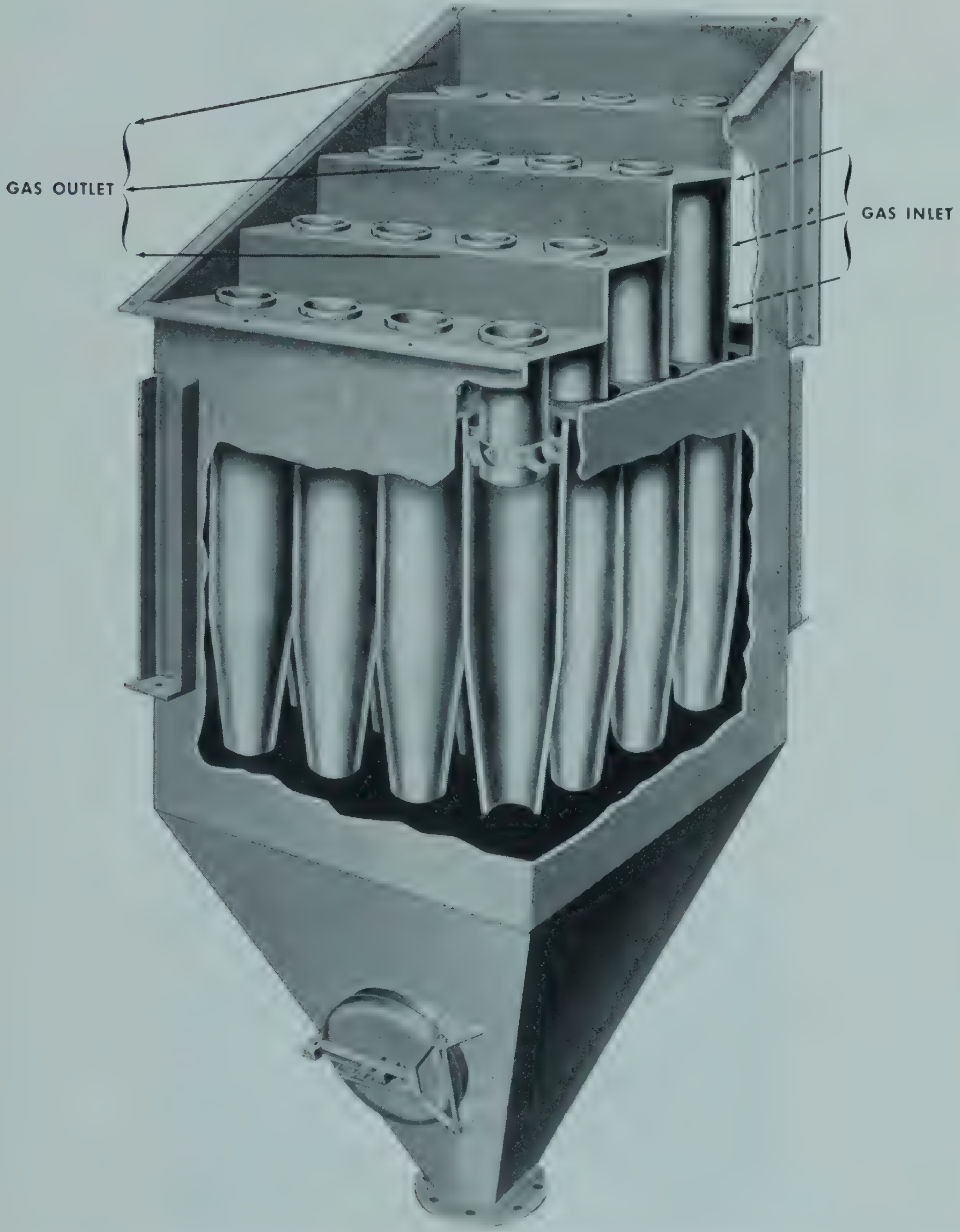

Figure 5. Multiple centrifugal separator. (Courtesy Western Precipitation Corp., Los Angeles.)

achieve more uniform distribution of particles throughout the medium, giving a slower rise in air-flow resistance and, therefore, longer filter life.

Resistance of Filters to Air Flow. Filters are characterized by increased resistance to air flow as the deposit of solid particles increases in amount. This has led to the development of mechanized or self-cleaning filters, to keep resistance

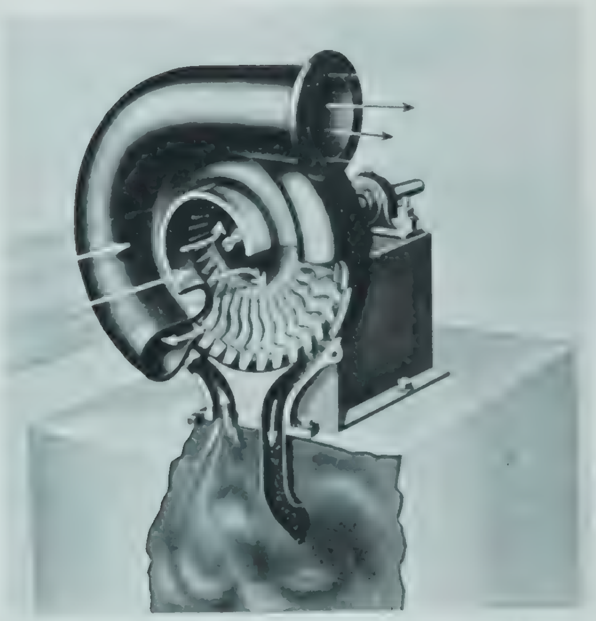

Figure 6. Rotary centrifugal separator. (Courtesy American Air Filter Co., Louisville.)

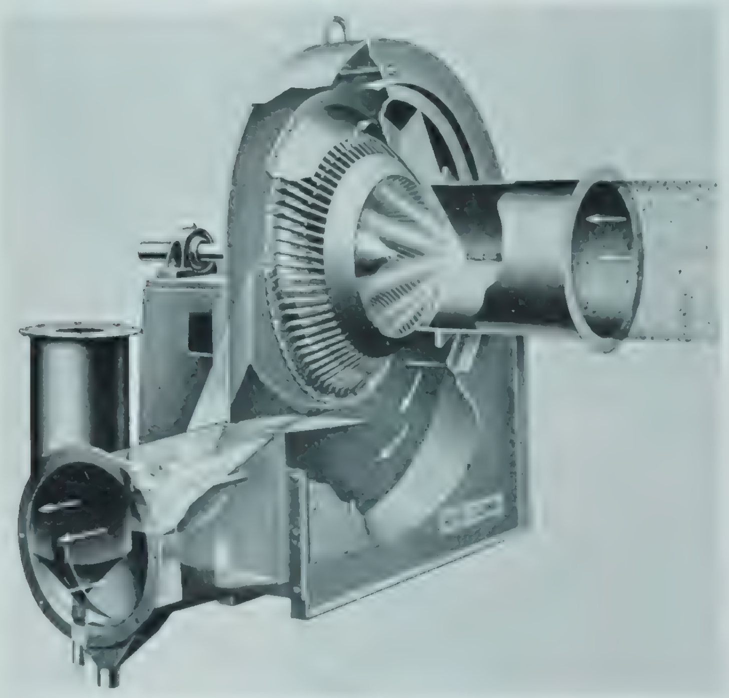

Figure 7. Rotary centrifugal scrubber. (Courtesy American Air Filter Co., Louisville.)

within practical limits. "Throwaway" units are discarded when the air-flow resistance becomes too great. Large industrial installations are provided with manual or automatic arrangements for dislodging the "filter cake" and restoring the pressure drop to a point near its initial value. It is best to provide some form of pressure-indicating instrument connected across the filter to give warning of excessive resistance that would reduce air-flow capacity or increase power consumption.

Separation ability is likely to increase as the accumulated deposit increases the internal air velocities by decreasing the pore sizes. At the same time, dust-holding capacity is limited by the permissible increase in resistance. Therefore, performance of filters should be specified in terms of initial and final pressure drop, dust-holding ability in weight per unit area or volume of medium, and initial and final separation percentage or degree.

Resistance through filters used for light duty in air conditioning ranges from 0.05 to 0.5 inch of water at velocities from 200 to 500 linear feet per minute, based on the gross area presented to the air stream. Industrial dust and fume filters, or cloth arresters, operate usually at resistances from 2 to 5 inches of water at velocities from 0.5 to 10 linear feet per minute. Hemeon[8] has reviewed the characteristics of these filters in some detail. The new "absolute" filters of feltlike structure composed of paper pulp and asbestos perform at velocities and resistances comparable to those occurring with cloth arrestors.

Filter Life. The life or period of service of an accumulating separator, such as a filter, depends upon the upper limit of resistance to air flow through the filter. This depends not only on the structure of the collecting medium, but also upon the size and shape of the particles in the deposit and the concentration of particles in the air stream.

The life expectancy of a filter may be expressed in terms of the accumulated weight of deposit per square foot of area of the medium that will result in a specified increase of resistance from the initial value to the maximum value at the required volume of air flow.

If the filter is the cleanable type, its service life depends in part on the ability to restore its resistance to a value low enough to give a workable margin below the allowable maximum pressure drop. Some media cannot be returned to their initial resistance because of the tenacity of collected particles. Eventually, the improvement by cleaning is so slight, or the interval between cleanings so short, that it becomes less expensive to install a new filter.

A. IMPINGEMENT FILTERS

Standard-size panel filters for air-conditioning or ventilating systems have been constructed of practically every material that can be formed into fibers, wires (Figure 8), perforated or expanded sheets, granules or beads. They remove particles from the air stream by a combination of screening, straining, or sieving; impaction or impingement; and surface attractive forces, chiefly electrostatic. Their mechanical design usually emphasizes straining and impingement and, accordingly, they exhibit best performance against coarse particles, and those having irregular shapes that are easy to capture in filters.

Impingement filters are available in metals, such as steel, bronze, and aluminum; and in nonmetals, such as glass, cellulose, rubber, animal hair, and as-

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[8] W. C. L. Hemeon, *Plant and Process Ventilation.* Industrial Press, New York, 1955.

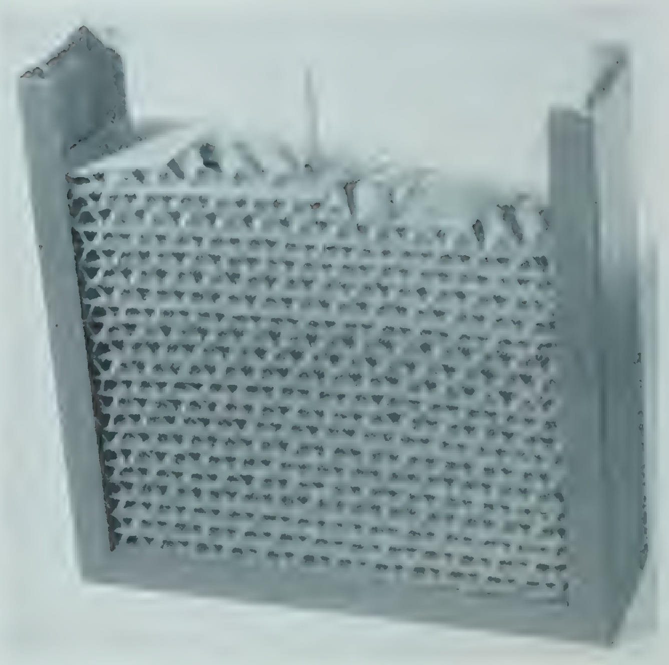

Figure 8. Impingement-type panel filter of wire mesh construction. (Courtesy Farr Co., Los Angeles.)

bestos. These materials may be combined to give a filter having highly specialized characteristics adjusted to the performance requirements of any application. They are usually placed in the position of precleaners when the air-cleaning system is designed to remove submicron particles to a high degree.

B. VISCOUS FILTER MEDIA

The tendency of dust particles to blow off the filter surfaces, due to air turbulence or excessive velocity, has led to the development of devices known as "viscous impingement filters." The collecting medium is treated with an oil or adhesive of correct physical and chemical properties so that particles once contacted will remain on the viscous surface. The adhesive material may be applied periodically as a step in restoring cleanable filters to effective service, or it may be applied continuously to a conveyorized medium passing through a liquid and sludge tank (Figure 9).

C. PAPER FILTERS

Separation of fine particles can be achieved by forcing the air stream through a paper-like filter medium of fairly porous construction. The conventional method of providing high air-flow capacity without creating excessive resistance is to assemble the paper or felted fibers in a "V" arrangement (Figures 10 and 11). The medium may be used in a single layer, or as a multiple-layer filter of uniform or variable density.

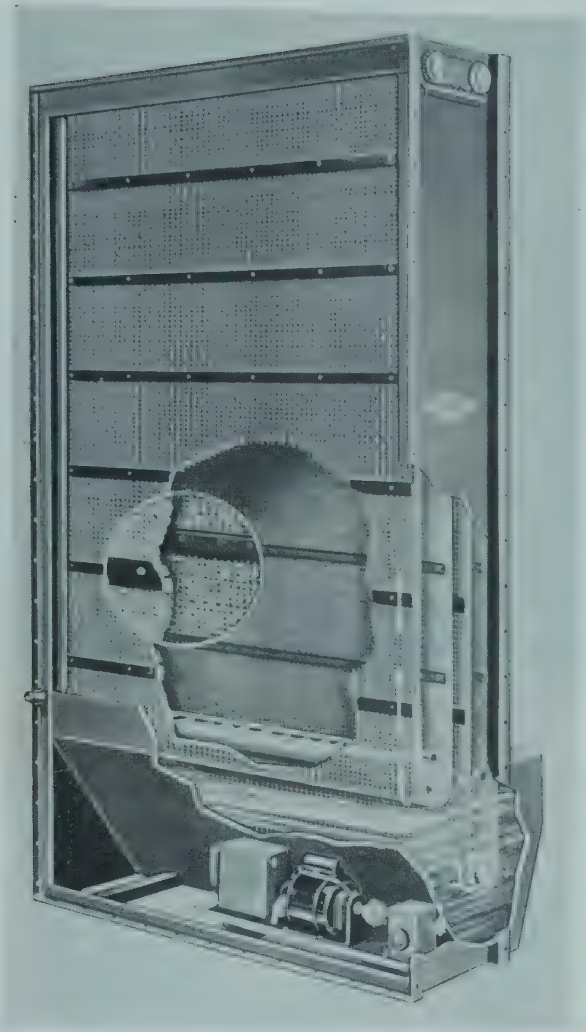

Figure 9. Conveyorized impingement-type filter. (Courtesy Dollinger Corp., Rochester, N. Y.)

The fibers in paper filters may be cellulose, asbestos, glass, ceramic, or any of the new synthetic organic materials. These same fibers can be packed loosely in a deep bed or mat supported across the air stream by a removable frame. As the size of individual fibers decreases, their contact surface area increases, improving the chances of intercepting particles in the air stream.

D. CLOTH FILTERS

The filter medium in dust or fume collectors may be cotton, wool, synthetic-fiber cloth, or glass-fiber cloth, generally of woven construction, although felted fibers can be used when properly supported. Cloth is placed in the air stream in the form of envelopes or sleeves over screen frames (Figure 12), round or oval tubes (Figure 13), or large cylinders held in shape by the air pressure (Figures 14 and 15). The fabric is mounted vertically to allow gravity to draw the accumulated dust cake down from the filtering zone into a hopper.

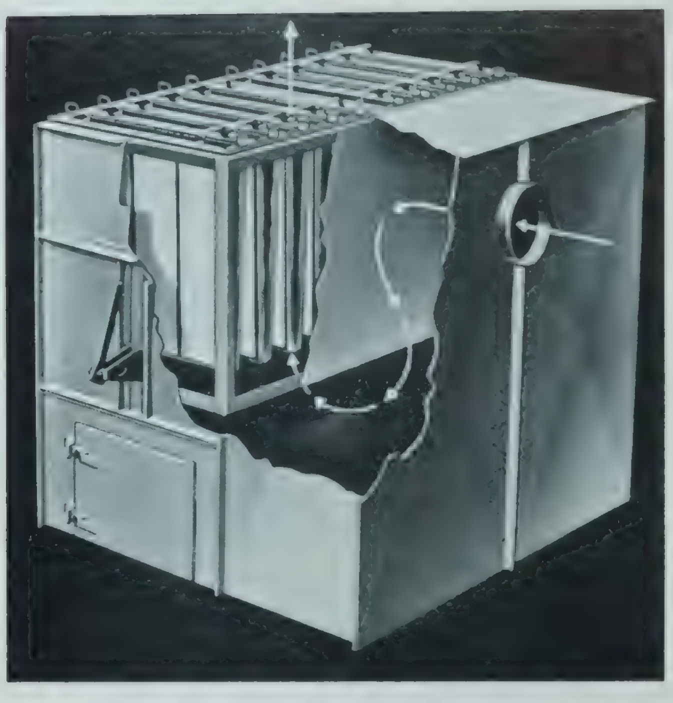

Figure 10. Paper-type air-filter assembly. (Courtesy American Air Filter Co., Louisville.)

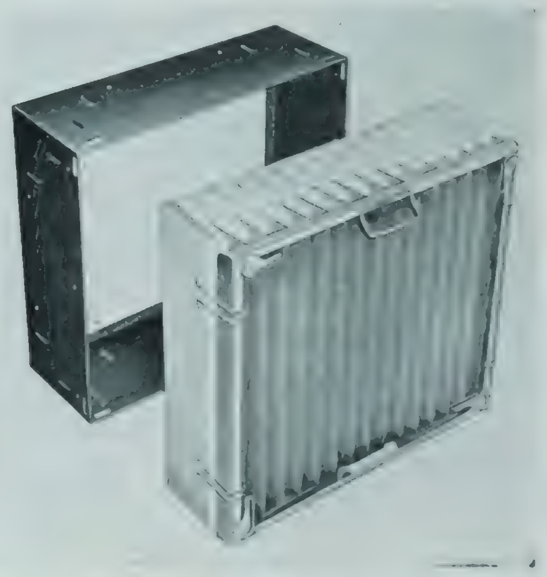

Figure 11. Air-filter unit designed for replaceable paper medium. (Courtesy American Air Filter Co., Louisville.)

Cotton cloth may be used against air or gas at temperatures up to 180° F.; wool can be used up to 225°; synthetic-fiber cloths (orlon, nylon) have various limitations on temperature in the vicinity of 300°; and glass-fiber cloth or asbestos cloth will withstand temperatures up to 600°.

E. ABSOLUTE FILTERS

The U. S. Atomic Energy Commission has encouraged the development of filter media so effective against fine particles that they have come to be known as "absolute" filters. With such materials it is possible to attain more than 5-degree filtration (above 99.999 per cent removal) even on a particle-count basis. These filters are of feltlike structure composed of paper pulp and asbestos.

Applications include the removal of radioactive particles, air-borne microorganisms, and irritating aerosols associated with smog. Superclean air can be supplied to enclosures provided for the manufacture of photographic materials, biological products, precision instruments, and optical devices. The demand for high-degree cleaning is certain to increase as the cost of such filters is reduced.

F. GAS OR VAPOR ADSORPTION FILTERS

Active carbon granules are arranged in layers, beds, or cylindrical canisters so that air may be filtered through and deodorized, decontaminated, or otherwise relieved of undesirable gases or vapors. At the same time, solid or liquid particles will be separated, and to avoid plugging the adsorbent granules, a preliminary stage of cleaning may be required.

Silica gel, activated alumina, and other solids may be used for adsorption filters, but at the present time specially prepared carbon is the material of choice for air-conditioning systems. It can adsorb practically all organic vapors of the kind responsible for odor nuisance, and it selects these substances from the air stream in preference to water vapor.

Adsorbed gases or vapors can be removed by regenerating the carbon by heat or steam, which may be done in position, or at another location. The perforated containers or canisters (Figure 16) designed for use in air-conditioning applications are easily removable for shipment to the regenerating plant, and a schedule of exchange is worked out to ensure continuously effective treatment of the air.

X. Electric Precipitators

If air or gas is passed through a high-voltage electrostatic field, suspended particles will acquire an electric charge and move through the air toward any object carrying an opposite charge. They will precipitate or collect at a point determined in part by the air velocity, the distance to the contact surface, and the attractive force. Air-borne particles of any size can be separated by electric precipitation, if they can reach and remain on the collecting electrode. The "ionized" gas molecules, of course, remain only long enough to discharge, and therefore cannot be removed by this process.

In practice, electric precipitation is designed to be specially effective against fine particles, usually those below 10 μ. Separation can be made 99 per cent complete (2 degrees); higher percentage of removal is generally not attempted be-

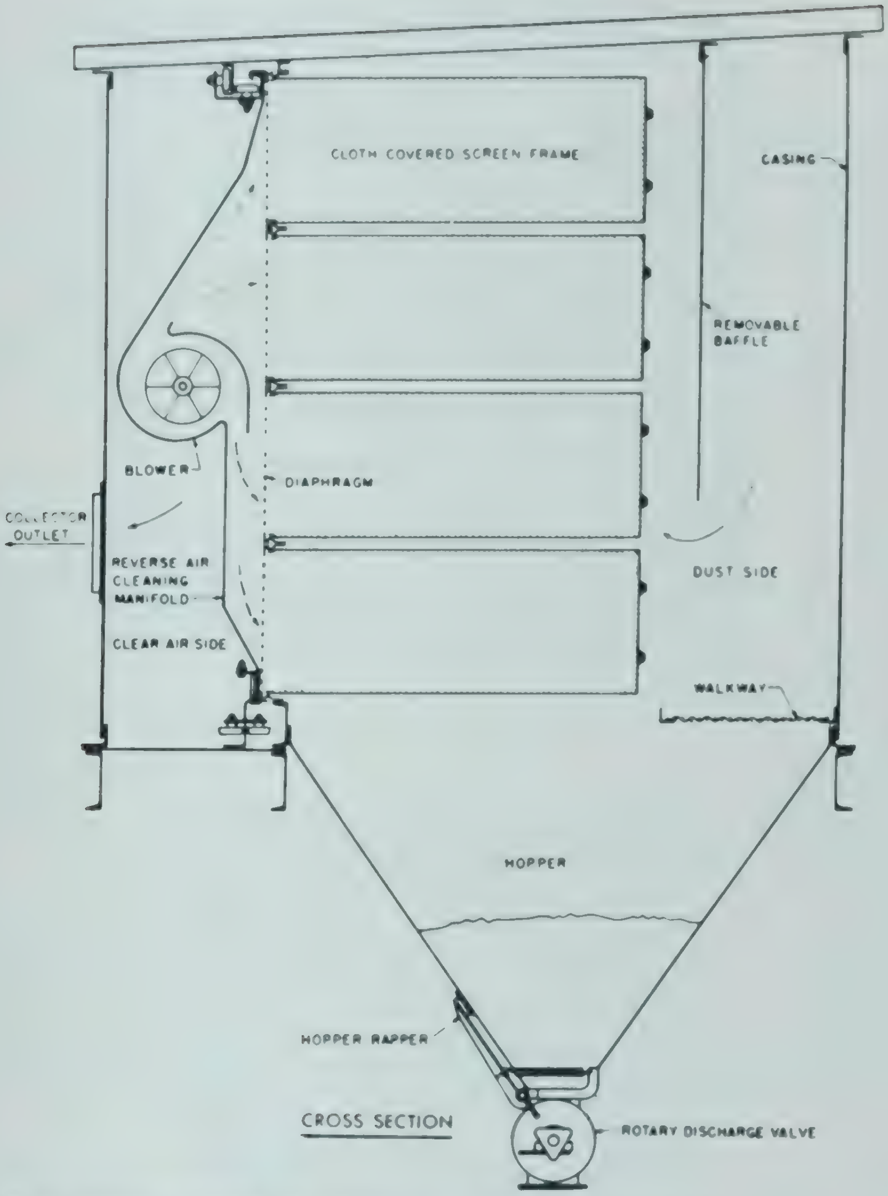

Figure 12A. Cloth-covered-screen filter assembly arranged for automatic reverse-air cleaning of filter fabric. (Courtesy Pangborn Corp., Hagerstown, Md.)

cause of the excessive space requirement, which increases approximately in proportion to the increase in effectiveness desired, specified on the degree scale (page 238).

Air velocities through electric precipitators are moderate; they are between those used for filtration with fabrics and those required for inertial separation. Accordingly, pressure drop is low, and wear due to abrasion is slight. At the same time, air distribution can be a problem with low velocities, and it may be necessary to provide distributing plates, dividers, or filters at the inlet to attain uniform approach to the charging and precipitating zones.

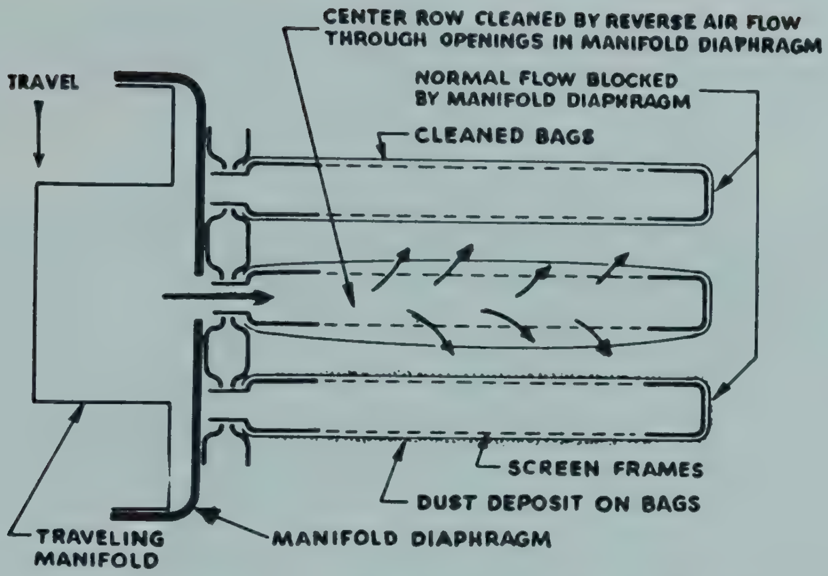
CENTER ROW CLEANED BY REVERSE AIR FLOW THROUGH OPENINGS IN MANIFOLD DIAPHRAGM
TRAVEL
NORMAL FLOW BLOCKED BY MANIFOLD DIAPHRAGM
CLEANED BAGS
SCREEN FRAMES
DUST DEPOSIT ON BAGS
TRAVELING MANIFOLD
MANIFOLD DIAPHRAGM

Figure 12B. Top view of reverse-air-flow mechanism for cleaning filter bags. (Courtesy Pangborn Corp., Hagerstown, Md.)

Electric Resistivity of Dust Deposits. Two electric properties of the deposit on collecting electrodes have an important effect on the performance of electric precipitators. These are (*1*) the conductivity or resistivity and (*2*) the breakdown or dielectric strength. The higher the dielectric strength of the dust layer, the less sensitive is the precipitation process to the effects of high resistivity.[9]

Humidification, using water vapor, is an effective method of reducing the resistivity of solid particles. Other vapors or gases, which in small concentrations also have the ability to reduce resistivity of specific dusts, may be present in the carrier gas or may be added as "conditioning agents." By experience and research, manufacturers of precipitators have learned about a number of such favorable combinations.

Adhesives used in precipitators applied to air-conditioning systems not only may improve the dust-holding ability of electrodes, but also may contribute to better performance by reducing the resistivity of the dust.[10]

A. SINGLE-STAGE HIGH-VOLTAGE PRECIPITATORS

Electric precipitators for removing solids or liquids from industrial process gases generally operate at voltages from 25,000 to 100,000, direct current. The discharge electrode system of rods or wires is maintained at a negative potential, and accordingly imparts a negative charge to particles suspended in the gas. The collecting electrode arrangement leads to the description of single-stage precipi-

[9] H. J. White, *Mech. Eng.*, **77**, 254 (abstract) (March, 1955).
[10] G. W. Penney, *Trans. Am. Inst. Elec. Engrs.*, **70**, 1009–1013 (1951).

tators as *plate type* (Figure 17) or *pipe type* (Figure 18). Particles attracted to the collecting plates or tubes give up all or part of their charge upon contact, and then fall into hoppers after being dislodged with rapping or vibrating mechanisms, or flushed down with water.

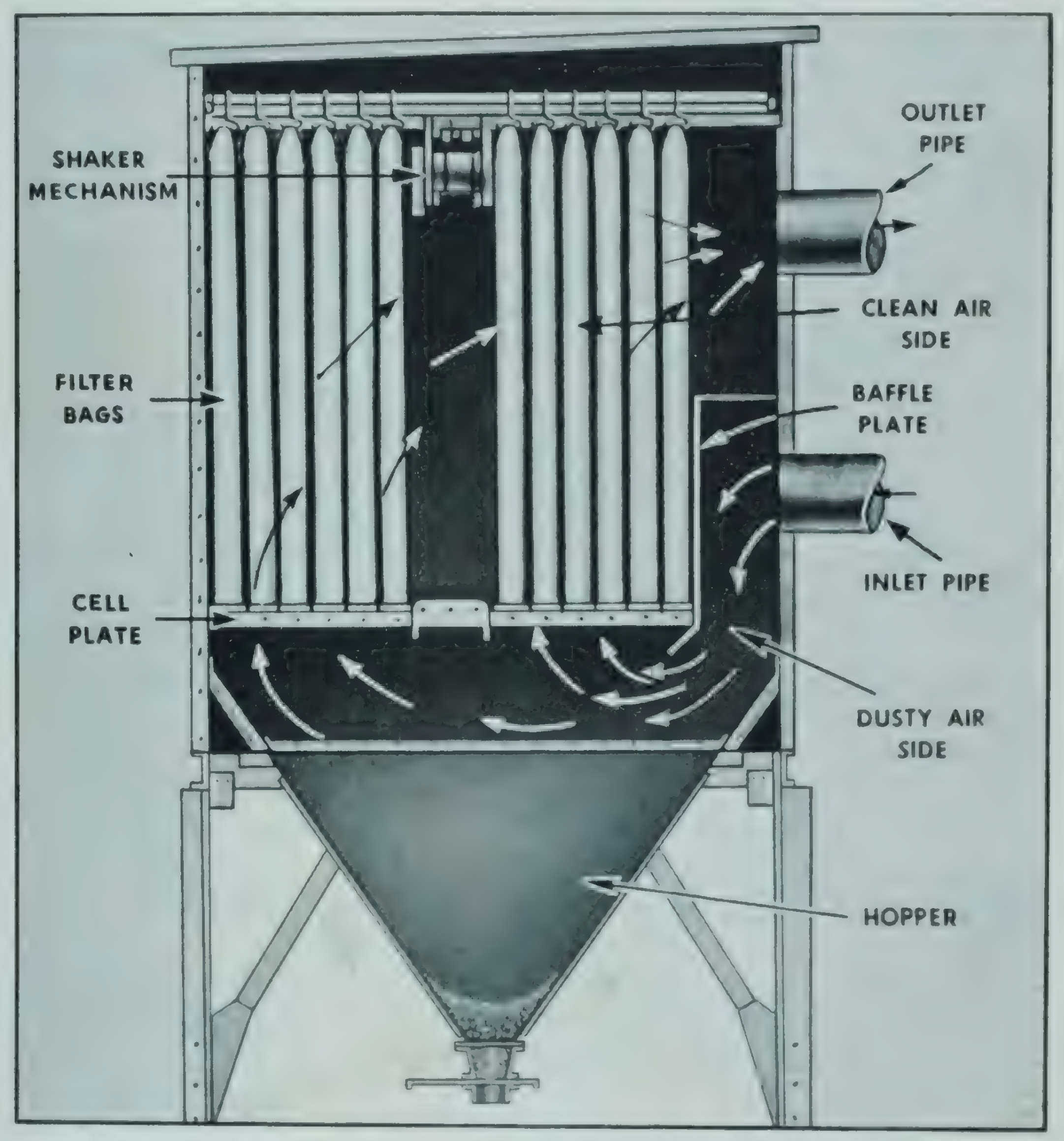

Figure 13. Cloth-bag filter assembly. (Courtesy Wheelabrator Corp., Mishawaka, Ind.)

Wet precipitators are usually of the pipe or tube design arranged for upward vertical gas flow, and operated at velocities low enough to prevent droplets from leaving with the outflowing gas. The tube-type precipitator is especially suitable for high-pressure or high-vacuum gas cleaning. Both tube and plate precipitators can be used in gas temperatures up to 1200° F., with appropriate construction materials.

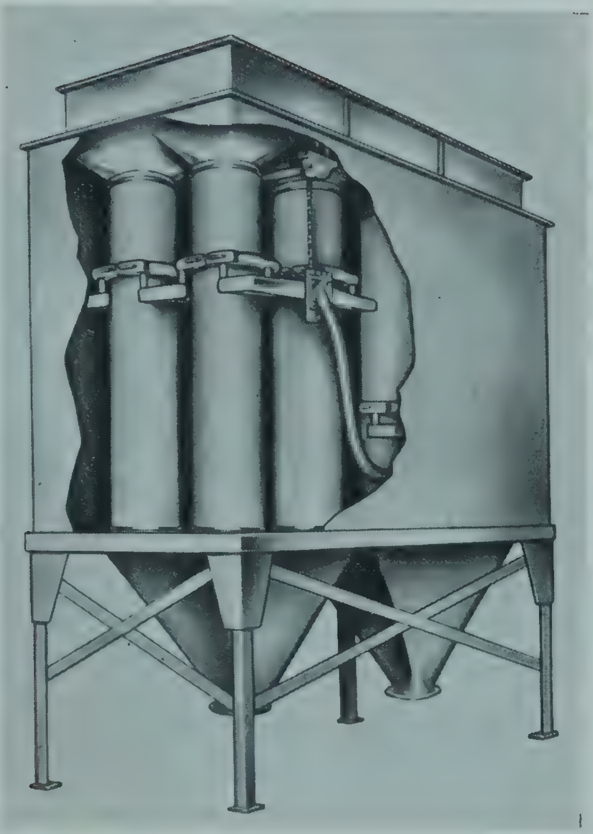

Figure 14. Cloth-tube filter assembly arranged for reverse-air cleaning of filter fabric. (Courtesy Turner & Haws Engineering Co., West Roxbury, Mass.)

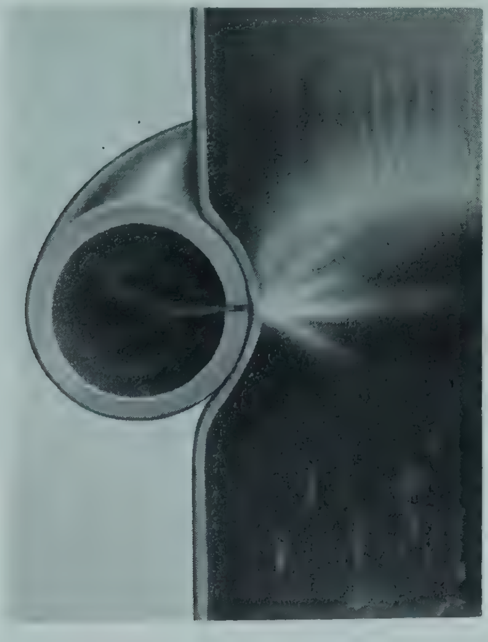

Figure 15. Diagram indicating action of blow ring against filter fabric in the process of removing dust accumulations by an air jet opposed to the main air current. (Courtesy Turner & Haws Engineering Co., West Roxbury, Mass.)

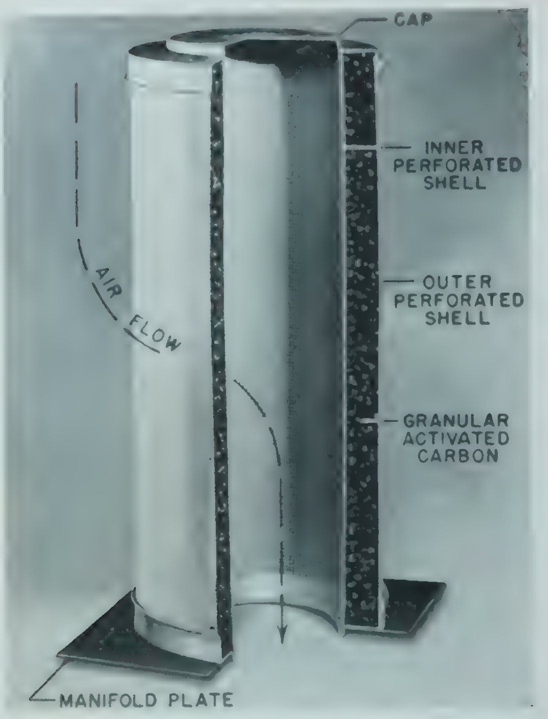

Figure 16. Activated carbon adsorber for gases or vapors. (Courtesy W. B. Connor Corp., Danbury, Conn.)

B. TWO-STAGE LOW-VOLTAGE PRECIPITATOR

To avoid the generation of excessive quantities of ozone and nitrogen oxides in air-conditioning installations, the charging and precipitating of air-borne particles are done at lower voltages in separate zones, or stages (Figure 19). About 12,000 volts are used for charging or ionizing the particles (preparation) and 6,000 volts are applied across the precipitating plates (separation). The alternate positive and negative collecting plates may be operated dry or may be coated with viscous material to improve dust-holding ability. If the precipitator is operated as a fog or mist collector, the plates are essentially self-cleaning, and the equipment has high continuity of performance.

Electric precipitators used in air-conditioning systems are not designed to operate against high concentrations of dust. It is good practice to install one or more stages of cleaning before the precipitator when the concentration of solid matter is more than about 1 grain per cubic foot of air. Because the collecting electrodes may accumulate dust or fume in clumps or aggregates that might return to the air stream, it is advisable in some applications to follow the electric precipitator with an "after" filter.

One design of electric precipitator for air conditioning combines electrostatic action with paper filtration. The paper is charged to attract air-borne particles, and may be installed as a continuous, slow-moving roll, presenting a clean section of paper to the air stream at a rate of travel based on the dust concentration and rate of air flow.

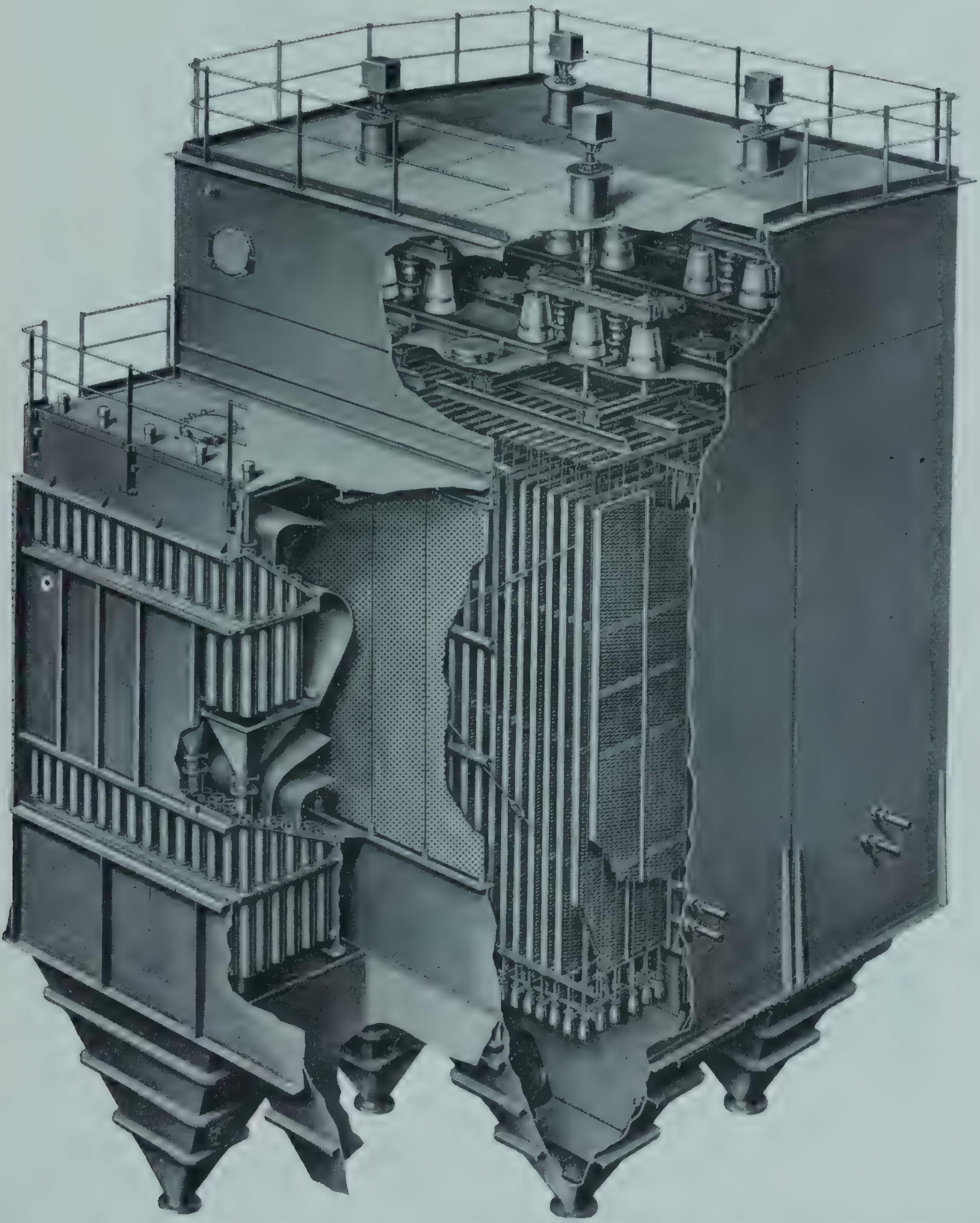

Figure 17. Perforated plate-type electric precipitator combined with multiple-tube centrifugal separator. (Courtesy Research-Cottrell, Inc., Bound Brook, N. J.)

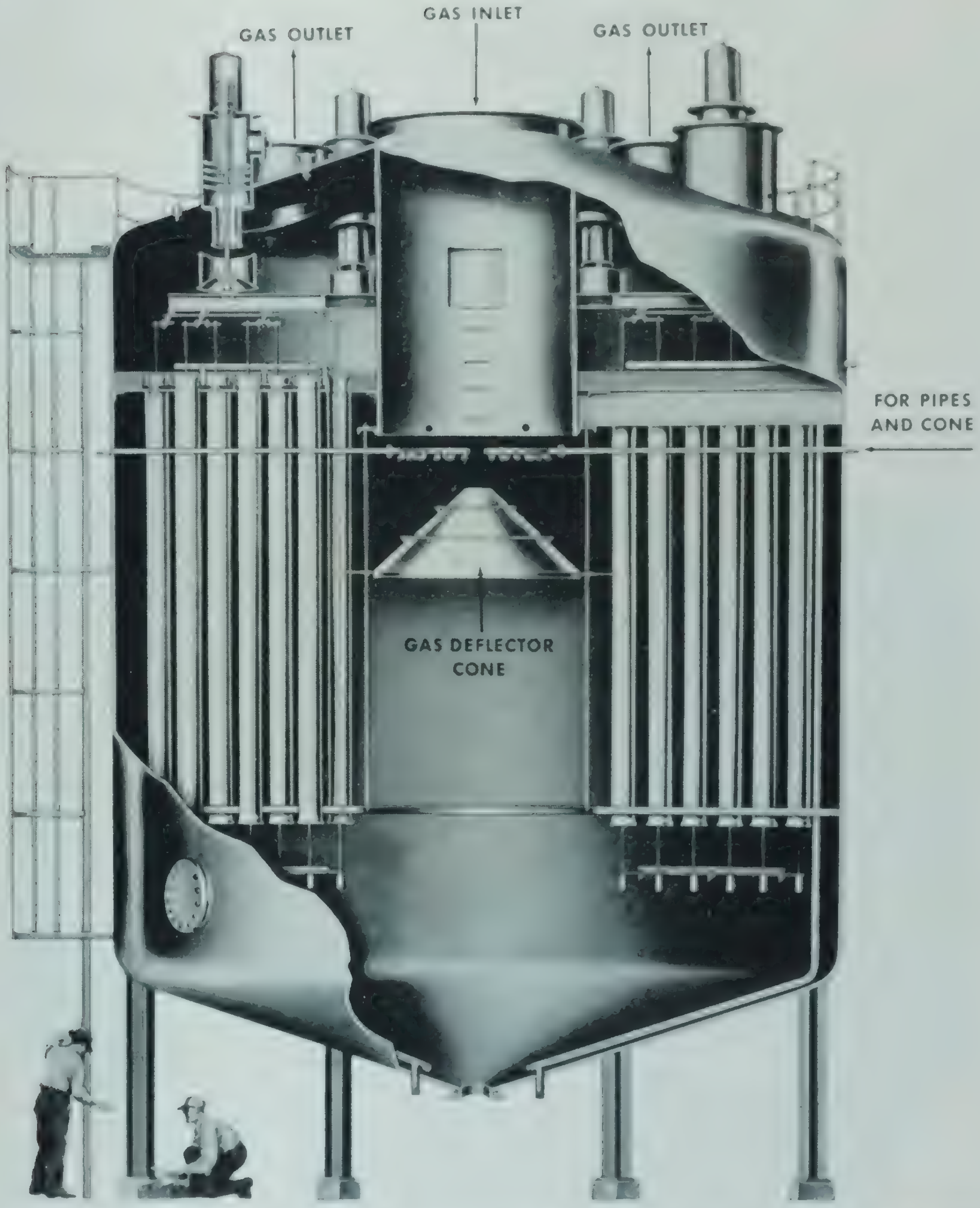

Figure 18. Pipe-type electric precipitator. (Courtesy Western Precipitation Corp., Los Angeles.)

Another design combines electric precipitation with automatic viscous filtration, in which the collector plates are continuously cleaned and reoiled by slowly passing through an oil bath and sludge chamber at the base of the machine.

XI. Washers or Scrubbers

The collecting surfaces of air-cleaning equipment may be dry, viscous, or liquid. When liquid is used, the cleaner is generally designated as a *washer* or

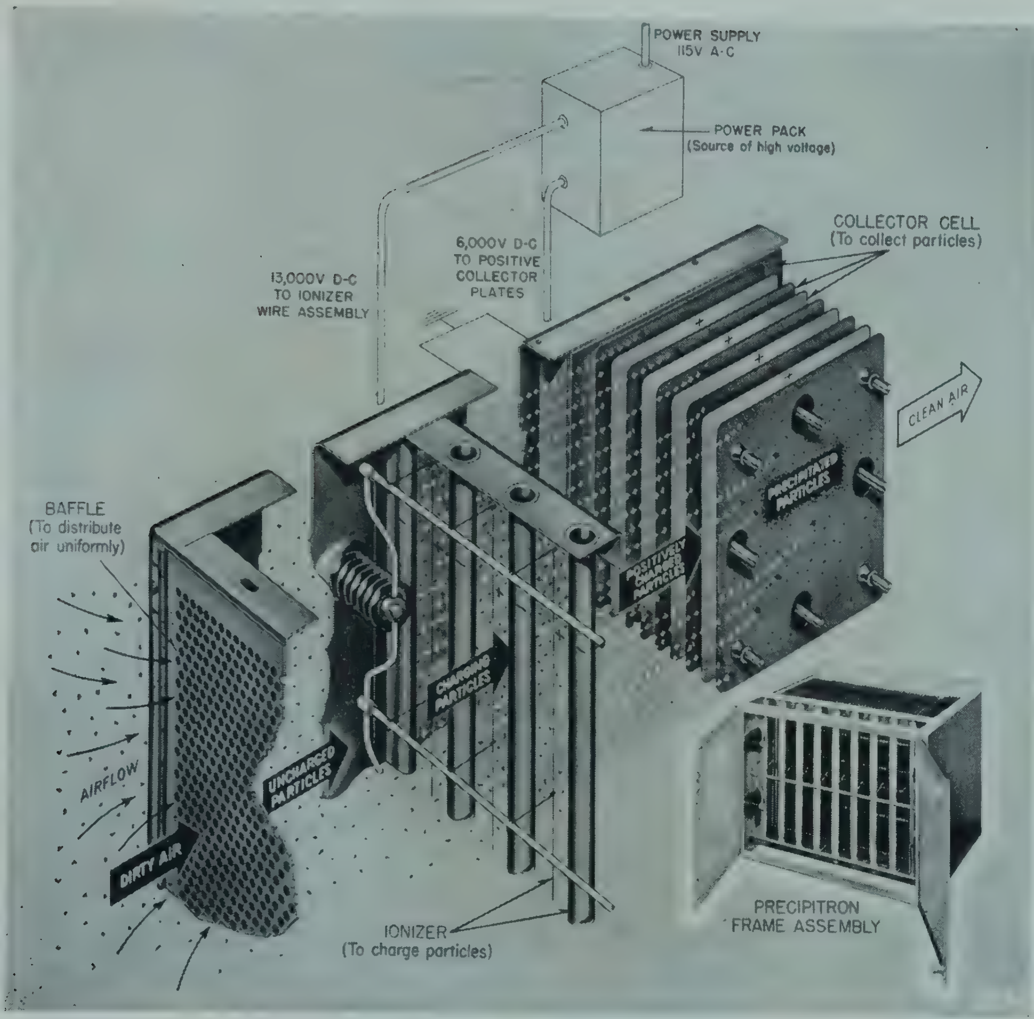

Figure 19. Two-stage electric precipitator for air conditioning. (Photo courtesy Westinghouse Electric Corporation, Sturtevant Division, Boston, Mass.)

scrubber. Nearly every type of dry mechanism for air or gas cleaning can be converted to a washer or scrubber by the use of a liquid. Furthermore, most wet systems can be operated dry, although generally with inferior cleaning ability.

There are some air cleaners that are almost entirely dependent upon liquid utilization, such as the spray of a liquid into a practically hollow chamber. Such equipment becomes essentially inoperative if the supply of liquid is interrupted. It may not fail completely, however, when other forces are present to a noticeable degree. Thus, gravity separation of heavier particles continues in a spray chamber after the flow of liquid is stopped.

Selection of Liquids for Scrubbers. Choice of a liquid for air or gas cleaning depends on the nature of the carrier gas and its constituents. Special attention should be given to these properties of substances to be removed from the gas:

1. Solubility in available liquids.

2. Reactivity with liquids and possible additives.
3. Acidity or alkalinity in water-base liquids.
4. Wettability by available liquids.
5. Sedimentability or floatability with specific liquids.

The liquid used most extensively is water, with or without chemical additives. Oils of low volatility are the principal alternates to water-base liquids. Highly viscous oils are not considered as air-washing liquids, but are used instead for treating the contact surfaces with an adhesive coating as a means of preventing entrainment of particles after their separation from the air stream.

One of the problems in the use of liquids for air or gas cleaning is the achievement of maximum contact between the liquid and the contaminant. Bubbling air through a liquid is effective only when the air stream is broken into bubbles small enough to give sufficient time for all the air in the bubble to encounter the boundary surface as it rises through the liquid. Air-sampling scrubbers of various designs make use of this mechanism, but the method becomes less attractive as the volume of air to be cleaned approaches the large quantities discharged from industrial processes.

It is more practical to inject liquid into the air stream at one or more points along its path from the source to the destination, using sufficient liquid to accomplish the required degree of air-liquid contact. The extent of liquid disintegration determines the amount of liquid surface exposed to the air. The problem is to create the finest possible droplets without causing an excessive carryout of fog or mist.

Liquid Contact Effectiveness. Air cleaning by means of diffusional forces, using a liquid, depends upon the effectiveness of film or drop contact with the air. When such contact is thoroughly intimate (Figure 20), the air and liquid will

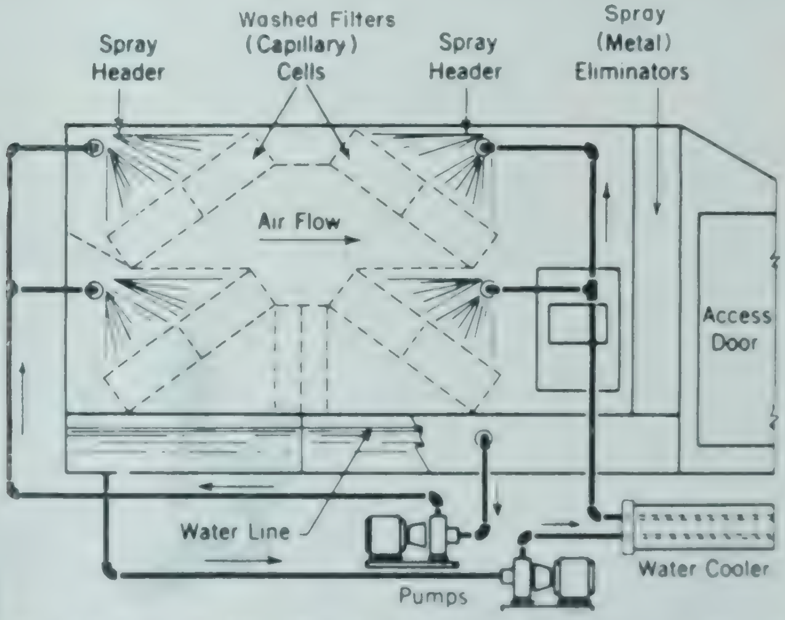

Figure 20. Filter-type air washer. (Courtesy Air and Refrigeration Corp., New York.)

leave the contact zone at essentially the same temperature, and the air will be saturated with the liquid. Saturation may then be used as an index of contact effectiveness and, thus, of cleaning ability. On the other hand, when a dust separator operates predominantly as an inertial device against particles chiefly above 10 μ in size, the liquid serves more as an adhesion treatment for contact surfaces and a hydraulic conveyor of the separated dust from the contact zone. In this case the approach to saturation of the air with vapor is not a reliable index of the effectiveness of separation.

Liquid Disintegration. The liquid may be atomized either by forcing it at high pressure through small orifices, or by flowing it into a high-velocity air stream. The "fog scrubber" (Figure 21) and "cyclone scrubber" (Figure 22) make use of the first method, and the "venturi scrubber" (Figure 23) the second. In any case, the degree of atomization depends upon the energy applied: to the liquid in the case of spray-nozzle scrubbers, or to the air in the case of venturi scrubbers.

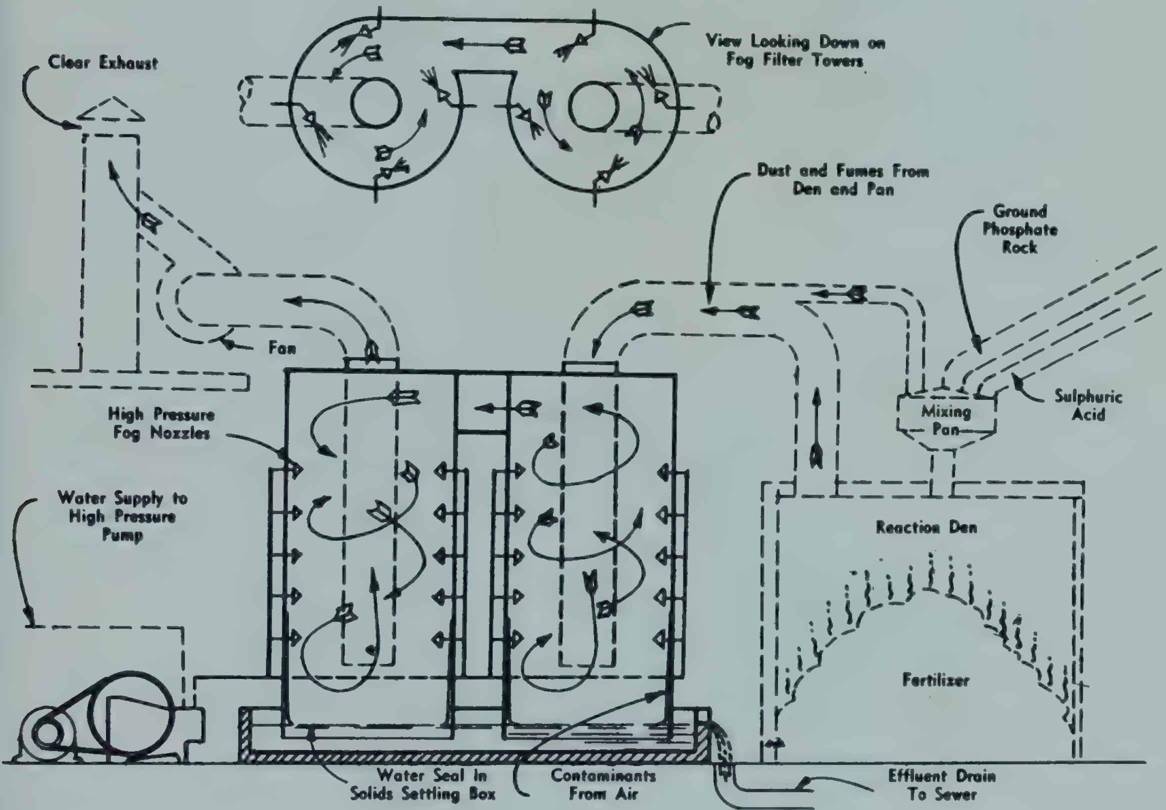
Clear Exhaust
View Looking Down on Fog Filter Towers
Dust and Fumes From Den and Pan
Ground Phosphate Rock
Fan
Sulphuric Acid
Mixing Pan
High Pressure Fog Nozzles
Water Supply to High Pressure Pump
Reaction Den
Fertilizer
Water Seal In Solids Settling Box
Contaminants From Air
Effluent Drain To Sewer

Figure 21. Double-tower fog-nozzle scrubber. (Courtesy Duncan Hudson, Birmingham, Mich.)

The amount of energy supplied to the liquid system ranges from 2 to 40 atmospheres, or 30 to 600 pounds per square inch. The highest pressures represent applications where extremely fine disintegration is desired for most effective cleaning or where a substantial amount of rotational energy is to be transferred to the air stream.

In the venturi system, the air pressure drop may be 20 or 30 inches of water. Air velocities in the throat of the venturi may reach 15,000 to 20,000 feet per minute, which are high enough to produce good disintegration of the liquid introduced at relatively low pressures.

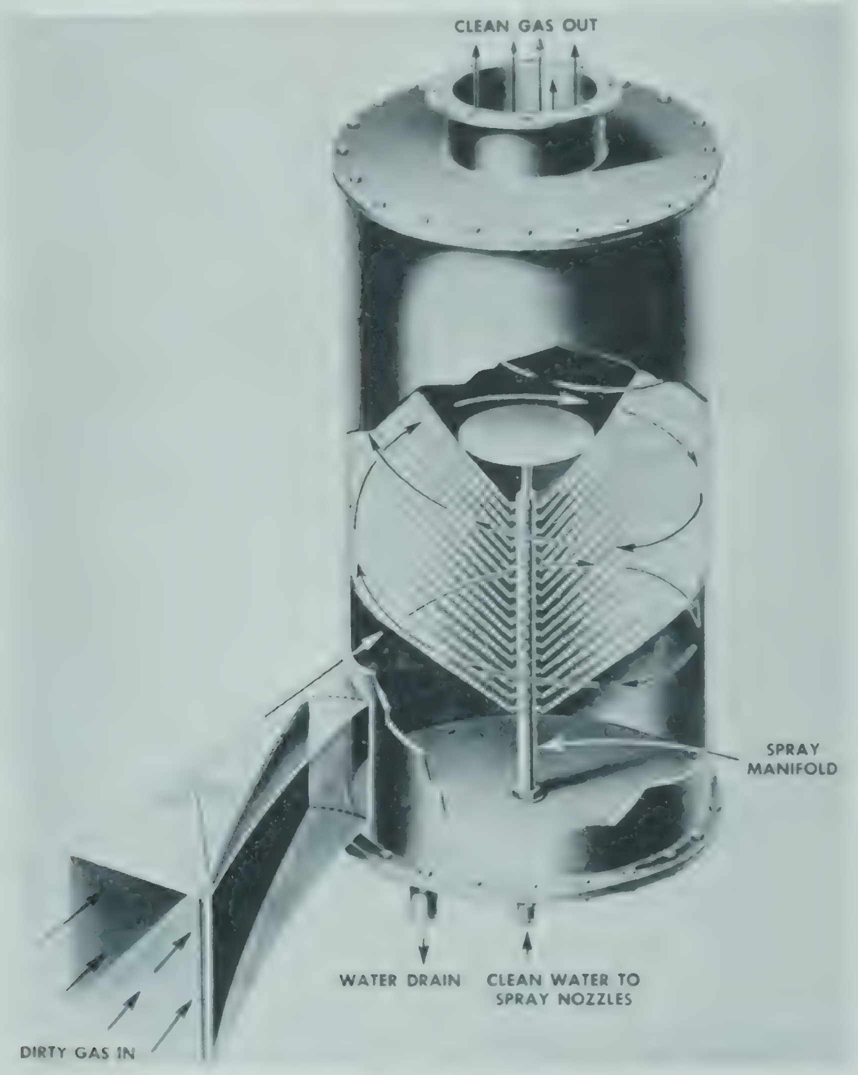

Figure 22. Pease-Anthony cyclone spray scrubber. (Courtesy Chemical Construction Corp., New York.)

The liquid may also be disintegrated by intense mechanical churning action, as in the rotary scrubber shown in Figure 24. In this case the energy of atomization, rather than being applied to the liquid or the air stream, is applied to the shaft of the mechanical disintegrator.

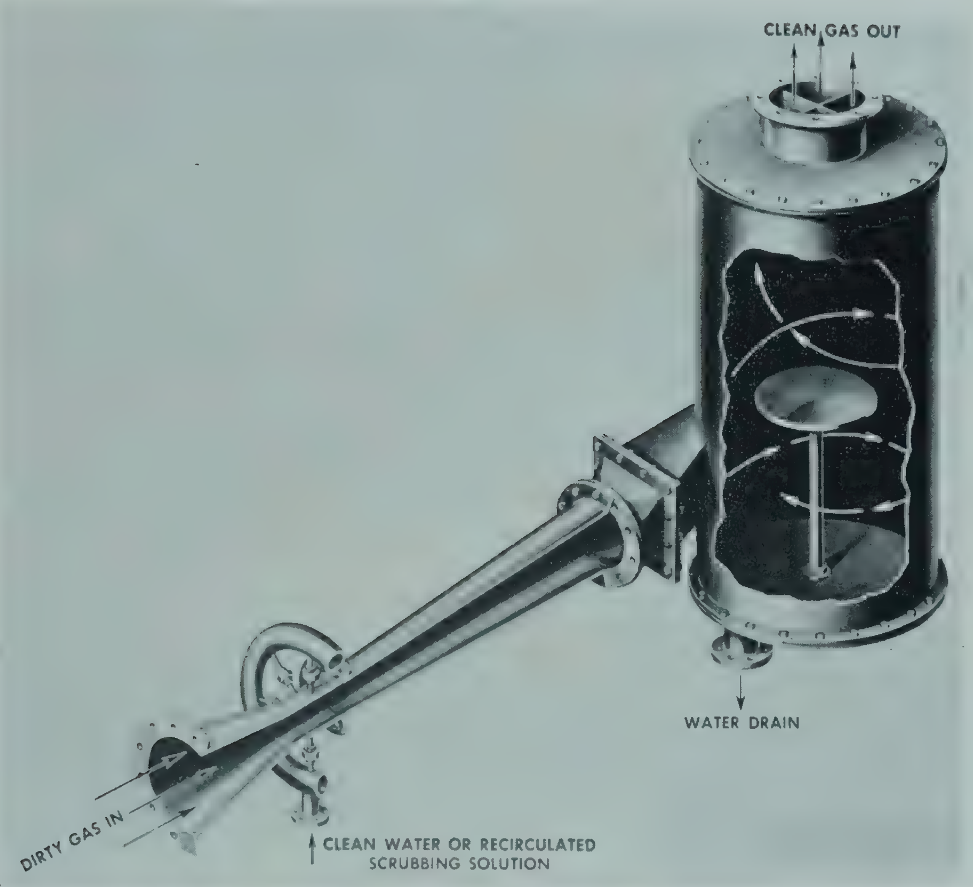

Figure 23. Pease-Anthony venturi scrubber. (Courtesy Chemical Construction Corp., New York.)

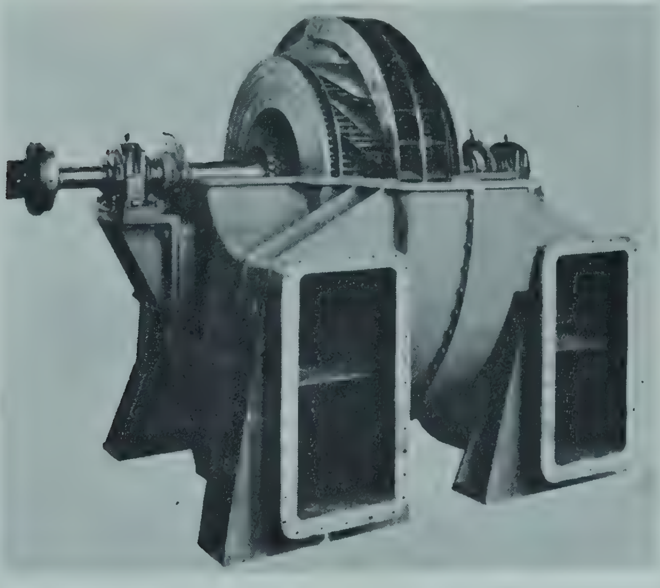

Figure 24. Mechanical disintegrating-type scrubber with top housing removed. (Courtesy Freyn Corp., Chicago.)

A. SPRAY CHAMBERS OR TOWERS

Air-washing equipment that depends on liquid sprays or cascades is characterized by empty or nearly empty enclosures through which air moves against fairly low resistance. The air-liquid contact surface is that of the liquid droplets as they fall through the air, supplemented by the surfaces of any deflecting elements placed across the air stream (Figure 25). As the air-liquid contact surface is increased by reduction of droplet size, a critical point is reached where the air stream begins to entrain or carry over the spray or fog. Spray pressure and nozzle type are therefore related to the velocity of air movement, and practical operation requires a compromise between high contact surface for most effective cleaning, and high air-treating capacity.

The spray chamber may be constructed as a vertical cylinder with tangential air inlet (Figure 25). Centrifugal force can be developed by the rotating air stream as a means of separating the liquid droplets and any large solid particles entering the chamber.

B. DEFLECTION ORIFICE SCRUBBERS

Figure 26 illustrates a type of air scrubber that makes use of energy in the air stream to generate a liquid spray or cascade. The "orifice" is the space between the surface of the liquid and a deflection element or "gate" below which the air must pass to reach the scrubbing zone. In some designs the air is impinged vertically against the liquid surface and escapes in all directions with the entrained liquid. Fully submerged impingement nozzles are used in gas-sampling instruments, but the impact velocities are far greater than used in air or gas cleaners of practical industrial design.

The orifice scrubber requires close control of liquid level to ensure the correct amount of liquid entrainment and, at the same time, prevent an excessive pressure drop, represented by depression of the liquid surface in the vicinity of the orifice. Pressure drop generally ranges between 2 and 6 inches of water.

C. PACKED TOWERS

Gas or vapor absorbers used extensively in the chemical industries are vertical cylinders or towers packed with materials like broken stone, hard coke, clay spheres, Berl "saddles"; or hollow cylinders or rings made of ceramic, metal, carbon, or glass, according to the chemical and structural properties required. Packed towers are remarkably effective as air cleaners when correctly designed and operated.[11]

The height of an absorption tower influences its effectiveness, while the cross-sectional area determines its air-handling capacity. For convenience in estimating capacity, the movement of air or gas through a packed tower is expressed in

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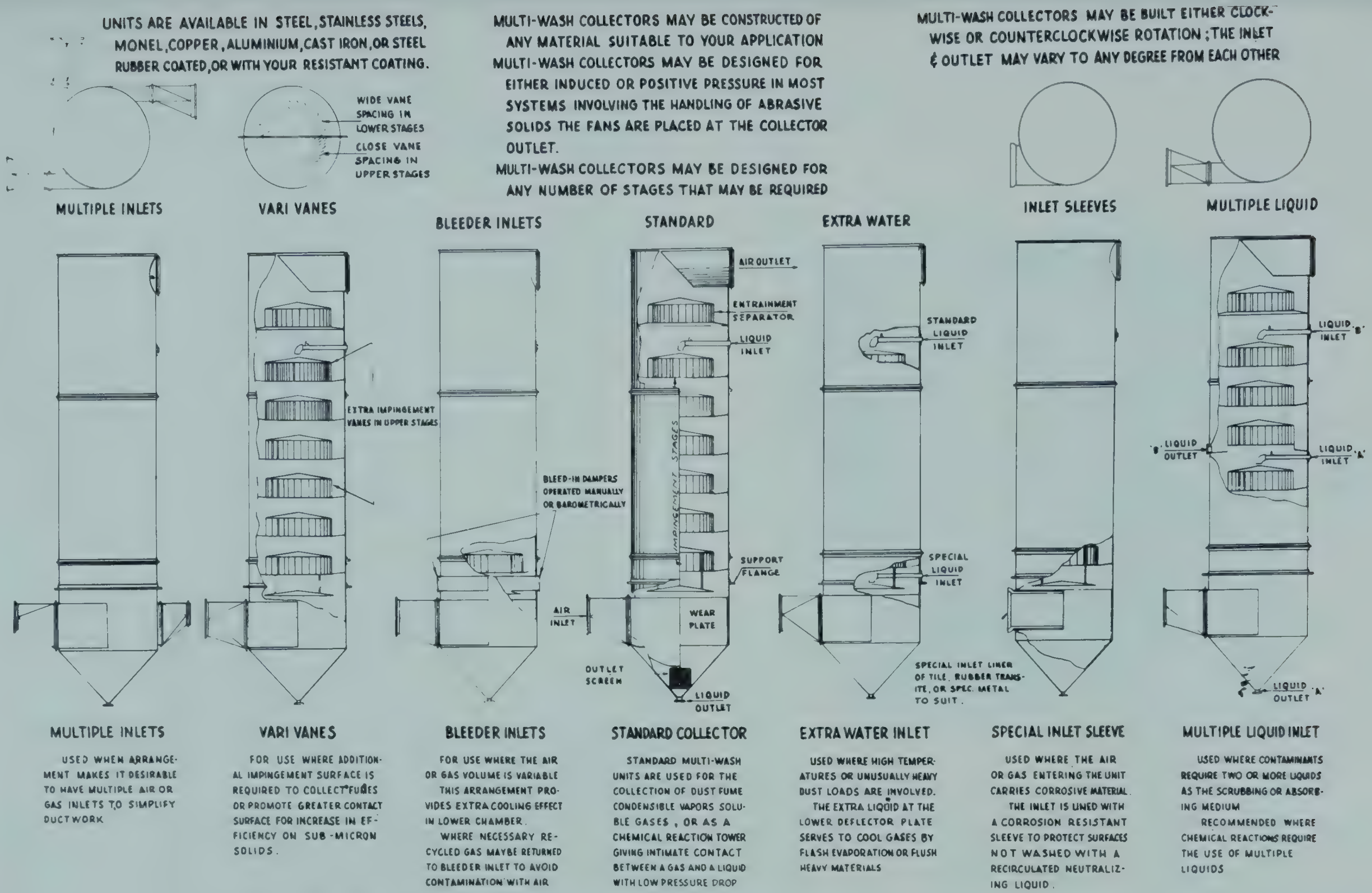
[11] Max Leva, *Tower Packings and Packed Tower Design*. The United States Stoneware Co., Akron, Ohio. 1953.



UNITS ARE AVAILABLE IN STEEL, STAINLESS STEELS, MONEL, COPPER, ALUMINIUM, CAST IRON, OR STEEL RUBBER COATED, OR WITH YOUR RESISTANT COATING.

MULTI-WASH COLLECTORS MAY BE CONSTRUCTED OF ANY MATERIAL SUITABLE TO YOUR APPLICATION

MULTI-WASH COLLECTORS MAY BE DESIGNED FOR EITHER INDUCED OR POSITIVE PRESSURE IN MOST SYSTEMS INVOLVING THE HANDLING OF ABRASIVE SOLIDS THE FANS ARE PLACED AT THE COLLECTOR OUTLET.

MULTI-WASH COLLECTORS MAY BE DESIGNED FOR ANY NUMBER OF STAGES THAT MAY BE REQUIRED

MULTI-WASH COLLECTORS MAY BE BUILT EITHER CLOCKWISE OR COUNTERCLOCKWISE ROTATION; THE INLET & OUTLET MAY VARY TO ANY DEGREE FROM EACH OTHER

MULTIPLE INLETS

USED WHEN ARRANGEMENT MAKES IT DESIRABLE TO HAVE MULTIPLE AIR OR GAS INLETS TO SIMPLIFY DUCTWORK

VARI VANES

FOR USE WHERE ADDITIONAL IMPINGEMENT SURFACE IS REQUIRED TO COLLECT FUMES OR PROMOTE GREATER CONTACT SURFACE FOR INCREASE IN EFFICIENCY ON SUB-MICRON SOLIDS.

BLEEDER INLETS

FOR USE WHERE THE AIR OR GAS VOLUME IS VARIABLE THIS ARRANGEMENT PROVIDES EXTRA COOLING EFFECT IN LOWER CHAMBER.

WHERE NECESSARY RECYCLED GAS MAYBE RETURNED TO BLEEDER INLET TO AVOID CONTAMINATION WITH AIR

STANDARD COLLECTOR

STANDARD MULTI-WASH UNITS ARE USED FOR THE COLLECTION OF DUST FUME CONDENSIBLE VAPORS SOLUBLE GASES, OR AS A CHEMICAL REACTION TOWER GIVING INTIMATE CONTACT BETWEEN A GAS AND A LIQUID WITH LOW PRESSURE DROP

EXTRA WATER INLET

USED WHERE HIGH TEMPERATURES OR UNUSUALLY HEAVY DUST LOADS ARE INVOLVED.

THE EXTRA LIQUID AT THE LOWER DEFLECTOR PLATE SERVES TO COOL GASES BY FLASH EVAPORATION OR FLUSH HEAVY MATERIALS

SPECIAL INLET SLEEVE

USED WHERE THE AIR OR GAS ENTERING THE UNIT CARRIES CORROSIVE MATERIAL.

THE INLET IS LINED WITH A CORROSION RESISTANT SLEEVE TO PROTECT SURFACES NOT WASHED WITH A RECIRCULATED NEUTRALIZING LIQUID.

MULTIPLE LIQUID INLET

USED WHERE CONTAMINANTS REQUIRE TWO OR MORE LIQUIDS AS THE SCRUBBING OR ABSORBING MEDIUM

RECOMMENDED WHERE CHEMICAL REACTIONS REQUIRE THE USE OF MULTIPLE LIQUIDS

Figure 25. Multiple-stage centrifugal scrubber. (Courtesy Claude B. Schneible Co., Detroit.)

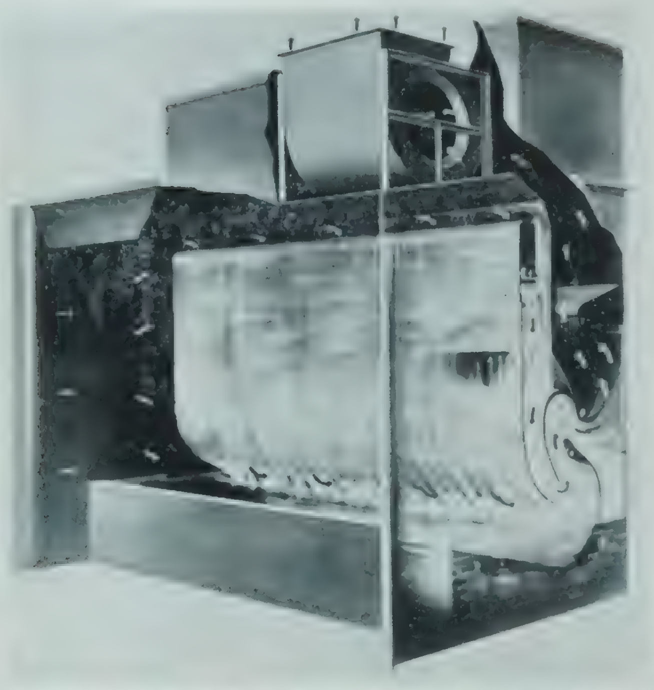


Figure 26. Orifice-type scrubber as used with paint spray booths. (Courtesy Newcomb-Detroit Co.)

terms of "superficial gas velocity," defined as the velocity that would occur if no packing were present. It is thus based on the gross cross-sectional area of the scrubbing tower or column. Superficial gas velocities generally range from 1 to 10 feet per second. Water or scrubbing liquid flow rates range from 100 to 10,000 pounds per hour for each square foot of gross area of the tower.

XII. Comparison of Dry and Wet Systems of Air Cleaning

A discussion of the relative merits of dry and wet systems of air cleaning may be out of order when recovery of materials is the objective. The required condition of the collected materials may settle the question promptly, and may dictate the use of a dry system when a balance of other considerations would lead to the application of a liquid. Therefore, the following summation of the advantages and disadvantages of both dry and wet systems applies chiefly to those cases where the air or gas is the product, or the air and its constituents are to be wasted in a condition meeting the requirements for air-, stream-, and ground-pollution control.

Advantages of Dry Systems

1. Solid materials are recovered in a form that may be utilized in the process or sold to others.

2. Sensible heat may be retained in the air or gas for transfer to other materials in a heat exchanger.

3. Highly effective dry systems can discharge completely clear gas to the atmosphere, without creating steam or fog during cold weather.

4. Flexibility of equipment location occurs as a result of the freedom from pumping systems, pipelines, and liquid storage tanks.

5. Equipment life is prolonged by minimum activity of corrosive air contaminants.

6. Accumulating cleaners, such as filters, may be disposed of by combustion without need of drying or evaporation of scrubbing liquid.

7. Freedom from the problem of liquid waste disposal is realized, provided that it is not subsequently necessary to combine the deposit with water as a dust-control measure.

Disadvantages of Dry Systems

1. Disposal of collected material may expose maintenance personnel to dangerous substances.

2. Accumulated dusts may present a severe fire hazard.

3. It may be necessary to use construction materials that will resist high temperatures.

4. Hygroscopic materials may cake or adhere to internal surfaces.

5. Condensation from humid gas may result in corrosion and cause plugging of the equipment with wet accumulations.

Advantages of Wet Systems

1. Greater versatility is exhibited on the particle-size spectrum, which includes the ability to remove gas and solids in the same equipment; natural method for capture of mists and fogs.

2. Entrainment of separated solid particles may be minimized.

3. Mass of some kinds of particles can be increased by wetting.

4. Decrease in temperature of gas may reduce its volume substantially and may prolong equipment life.

5. Heat content of gas may be partially transferred to the liquid for use elsewhere in the plant after clarification.

6. Fire or explosion hazard may be suppressed.

7. Abrasive effect of solid particles may be reduced by the lubricating effect of the liquid.

8. Hygroscopic solids can be handled, with sufficient liquid flow.

9. Condensation from humid gas may improve performance against submicron particles.

10. Liquid composition may be varied for flexibility of gas treatment.

11. Several liquids can be applied sequentially in some designs of scrubbers.

12. Anticorrosion treatment can be incorporated in the circulating liquid to prevent "cementation" of solid particles by oxidation.

13. Continuity of performance can be maintained by hydraulic removal of deposits from the zone of separation.

14. Deposits can be conveyed over long distances for installations having a large number of components; disposal of accumulated matter can be centralized, and the gas-treating liquid clarified for recirculation to the cleaning system.

Disadvantages of Wet Systems

1. Severe local restrictions on stream pollution may require costly treatment or disposal procedures for the liquid.

2. Water supply may require clarification or softening to prevent excessive maintenance down time.

3. Destructive activity of gas and constituents on the cleaning equipment may be increased in the presence of a liquid.

4. Humidity of delivered gas may be increased excessively.

5. Accumulated material may cause excessive foaming and entrainment of liquid droplets.

6. Small solid particles may be returned to the air stream if recirculated liquid is injected at high pressure to give good disintegration.

7. Freezing may occur in cold climates during shutdown periods; design and construction must provide for effective flushing and drainage to prevent freezing and minimize corrosion.

XIII. Combination Systems of Treatment

As we learn more about the correct application of numerous devices to the problems of air cleaning, the tendency is to assemble a number of complementary or supplementary units into an effective combination system. Selection of the best combination and sequence of preparation and separation elements depends heavily on the lessons of experience, but excellent results can be achieved by careful analysis of the contaminated air or gas to be treated.

A good example of a combination system is the inertial-electrical separator, applicable where a wide range of particle sizes occurs in the gas, or where dust loadings are high. An arrangement of this sort is shown in Figure 17.

Two principal arrangements of multiple-unit air-cleaning systems are recognized: parallel combination, and serial combination. Parallel combination is simply a means of providing a wide range of flexibility in adjusting the capacity of a system to the air-flow rate. It permits small, highly effective elements, such as centrifugal tubes, to be assembled in parallel arrangement for handling equal shares of the total air flow. Serial combination presents the problem of determining the best sequence, if different types of cleaning units are to be used, or the best combination of preparation and separation units, to meet the range of contaminants that must be removed from the air stream (Figure 27).

A. SEQUENCE OF SEPARATING STAGES

The selectivity of separators, or their fractionating tendencies, makes it advisable to combine stages of cleaning that are complementary. The sequence of treatment is generally, but not invariably, from the types of separator least able to remove submicron particles to those at the final stages most likely to succeed at this task.

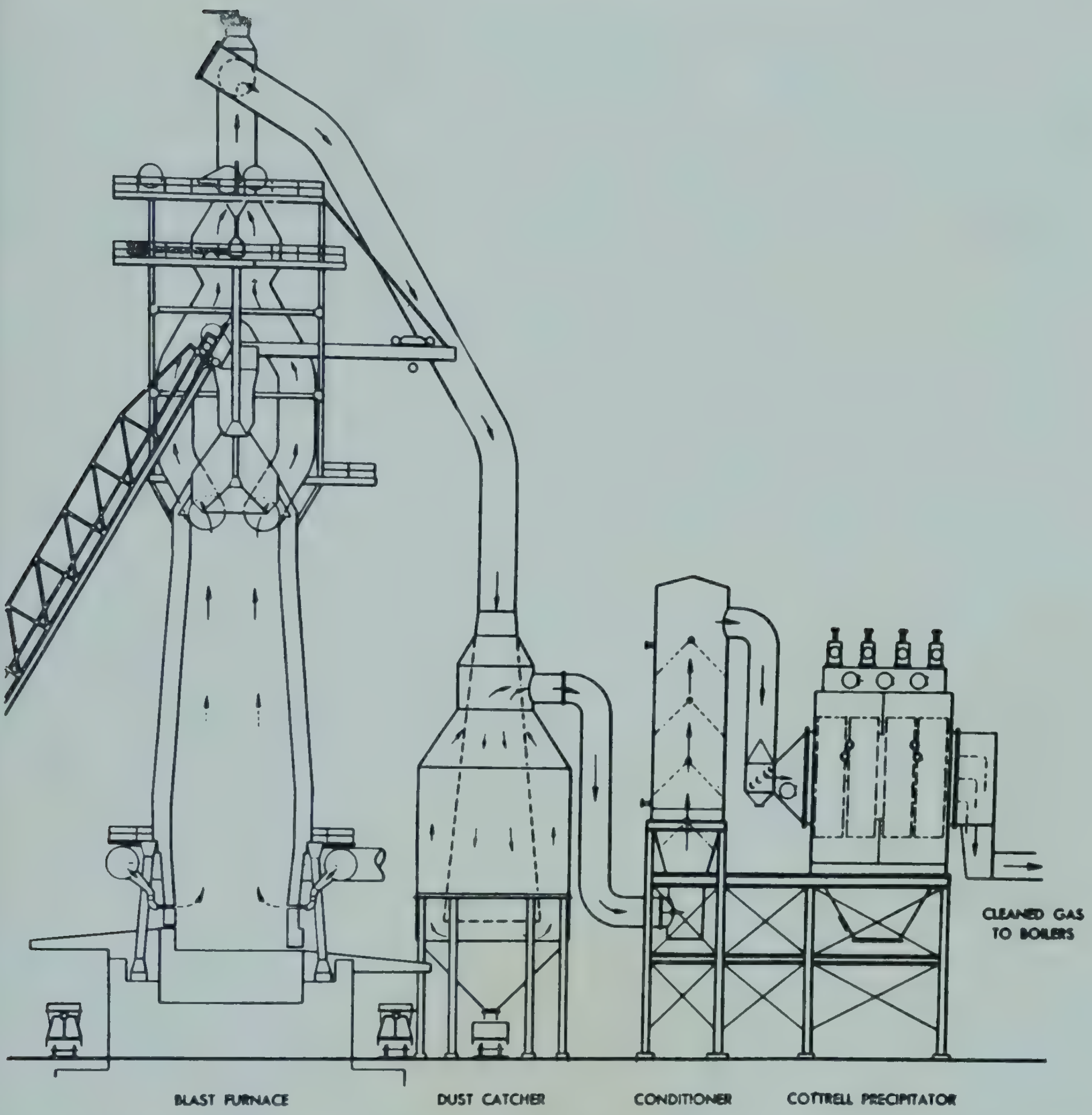


Figure 27. Combined gas-cleaning system applied to ferromanganese blast furnace. (Courtesy Western Precipitation Corp., Los Angeles.)

The agglomerating action of certain types of separators results in large aggregates or flocs blowing intermittently from dry collecting surfaces into the air stream. When this condition occurs, because of excessive air velocities or poor retentivity at the contact surfaces, it is good practice to interpose coarse-particle separators to reduce the load on subsequent stages of air cleaning.

Some of the variation in air-borne matter is gradually suppressed or damped as the air progresses through a multistage system of cleaning. While the process fluctuations may not be eliminated, they frequently are so modified in the initial stages of air treatment that the final, and most critical, stages are protected against disturbing variations in the character of materials traveling with the air.

B. TWO-STAGE CLEANING SYSTEMS

A natural outgrowth of the classification shown on page 240 is a basic two-stage system comprising a preparation stage and a separation stage. There are a number of well-known examples of this arrangement now in use: (*1*) two-stage electric precipitator, with particle charging preceding precipitation (Figure 19); (*2*) venturi scrubber, with simultaneous agitation and liquid injection preceding cyclone separation (Figure 23), (*3*) sonic agglomeration systems, with simultaneous agglomeration and gravitational precipitation followed by inertial or centrifugal separation. In the third example, preparation itself may occur in two stages, when fog is injected at the entrance to the sonic chamber to improve the cohesive property of particle aggregates.

C. CONCENTRATORS: SUBDIVISION OF AIR STREAMS

As the air passes through a cleaning system, it may be handled as a single stream from inlet to outlet. There are numerous installations, however, in which the air stream is subdivided one or more times in order to specialize the task of cleaning and make each stage more effective. A common example is conveyance of the small-volume high-concentration effluent from the apex or periphery of a cyclone to a secondary separator generating greater centrifugal force. In such cases the primary cyclone may be designated as a *concentrator*. The louvered cone separator described earlier (Figure 3) is also a concentrator from which a small fraction of the air flow is directed to a centrifugal separator for more complete removal of air-borne particles.

XIV. Entrainment Prevention

In dust-collecting problems, the attention of air-cleaning engineers has been focused almost entirely upon the forces of separation, with little attempt to bring the dust-raising or entraining forces into view. As a result, there is practically no reliable published information, at this time, on the action of separating devices as dust-suspending mechanisms, which most of them are to some extent. Interest in this problem may begin with a consideration of studies dealing with the dust-raising ability of winds in open air, and with the action of controlled air jets impinging against dusty surfaces.

In the absence of dust-entrainment data for a specific separator, the engineer tries to get the dust-accumulating surface rapidly away from the turbulent air stream. One of the easiest ways is the application of a liquid film that can be carried off by gravity or centrifugal force.

A. AIR TURBULENCE

Although air turbulence can be quite helpful in diffusional and contact processes, it is generally damaging in inertial and impact processes where control of the particle trajectory is desired. In diffusional processes, increased turbulence facilitates the approach to equilibrium at the interface or boundary between the air and the solid or liquid separating material. In inertial processes, the probability of resuspension or entrainment of particles increases as air velocity increases, with its resulting increase in air turbulence. Therefore, the use of increased air velocity to improve separation by higher centrifugal forces makes it necessary to arrange deflecting surfaces so that air may turn at high speed over smooth surfaces encountering a minimum of irregularities that cause air turbulence and particle entrainment.

B. VISCOUS LIQUIDS OR ADHESIVES

Separating surfaces may be treated continuously with liquids to improve retention and facilitate disposal of accumulated solids. They may also be treated periodically with liquids of relatively high viscosity that remain on the surfaces until removed by cleaning or regenerating procedures. Accordingly, the desired properties of the adhesive are influenced in large measure by the design and operating features of the separator or filter. Nevertheless, it is possible to state the desirable characteristics in general terms so that application engineers may be on guard in their selection of viscous liquids or adhesives for special duty.

Desirable Characteristics of Separator Adhesives

1. Viscosity should vary only slightly within the specified range of operating temperatures.
2. Viscosity should be low enough to permit a continuous flow of liquid in recirculating systems.
3. Surface tension should be sufficient to maintain an even film over the contact surfaces, prevent draining of liquid from upper portions of the medium in conveyorized systems, and prevent carry-over of mist.
4. Surface tension should not be high enough to inhibit the penetration of solid particles.
5. Capillarity should be sufficient to keep the exposed surfaces of the deposit wet.
6. Volatility should be low.
7. Adhesive should be odorless at the maximum operating temperature, when treating air for human consumption.
8. Adhesive should be fire-resistant, and preferably nonflammable, to prevent smoke panic and damage.
9. Adhesive should inhibit or prevent the growth of spores or bacteria.
10. Solubility in water is desirable to facilitate the cleaning of collecting surfaces.

XV. Continuous Service Arrangements

There is a growing demand for air-cleaning systems having steady and continuous performance characteristics, and the ability to operate for long periods of time without interruption for regeneration or removal of collected materials.

In some cases, the separating equipment has inherently high continuity of performance. Cyclones or centrifugal tubes provide highly continuous service when the separated solids or liquids have free-flowing characteristics. This feature of centrifugal apparatus has contributed to its popularity in materials-recovery applications.

Automatic disposal arrangements are now available for practically every type of cleaning device. It is also possible to incorporate midget separating mechanisms in an increasing variety of automatic recording, indicating, and controlling instruments to ensure continuous service of air-cleaning systems at the highest level of performance.

A. TEMPORARY REMOVAL FROM SERVICE

A conventional method of maintaining continuity in large filtration or electric precipitation systems is the temporary removal from service of one of the units in parallel combination. Capacity of the system is generally designed so that one or more units may be disconnected from the air stream without causing an excessive burden upon those remaining in service. This method causes a greater investment for equipment as well as consumption of space. Therefore, it is limited to those applications in which the size of the total installation is sufficient to permit a slight additional investment and space use for the continuity objective.

B. CONVEYORIZED OR RECIRCULATING SEPARATOR ELEMENTS

An effective method of achieving continuity of separation is conveyorizing the system so that accumulating surfaces are continuously removed from the separating zone. This feature is found in conveyorized filters (Figure 9), rotating disc or cylinder elements, and electric precipitator cells that travel down into liquid baths and return upward to the separating zone. Continuous feeding of a filter medium from a clean roll through the separating zone and onto an accumulating waste roll is another example.

Granular media may be conveyorized and recirculated so that separation of deposited matter from the filter packing can be accomplished in a space apart from the zone of air cleaning.

Transfer of solid sorbents from a separating zone to a zone of regeneration or reactivation may be accomplished by continuous or intermittent machinery. Fluidized systems lend themselves to this method of providing continuity of disposal. The active particles may be bled from the system continuously for regeneration or replacement.

C. REVERSE-AIR CLEANING OF FILTER FABRICS

An interesting means of incorporating continuous operation of fabric filters is that of reverse-air cleaning of the fabric. A small stream of air is blown through the medium in the direction opposite to that of the main air current. In one system, blow rings containing a narrow slot for the reverse-air jet (Figure 14) are carried by a chain or cable drive up and down the fabric cylinder, either continuously or intermittently. The resulting pressure flexing of the fabric (Figure 15) causes part of the deposit to disengage from the filter and fall into the storage hopper. This action returns a portion of the deposit to the air stream for reseparation, but the pressure drop and separation effectiveness are kept steady, resulting in highly continuous performance.

Another system of reverse-air cleaning of cloth filters is shown in Figure 12. In this case, each cloth envelope and metal screen unit is subjected individually to reverse air flow by a small blower that travels slowly from unit to unit.

A recent system of reverse-air cleaning of a filter makes use of a small jet of high-pressure air forced intermittently through a venturi into the upper end of a filter tube. This induces a momentary reversal of air flow, which blows off the deposit.

XVI. Waste Disposal

One of the troublesome problems facing the designer and operator of a gas-cleaning system is the ultimate destination of accumulated wastes. The amount of solid wastes that can be deposited continuously on nearby private or community dumps is by no means unlimited in most industrial areas. Dumping in lake or sea is available only at coast lines, and cannot be conducted without regard for water inhabitants, if the waste materials are poisonous. Burial or pumping into the ground may cause obnoxious or toxic materials to enter the ground water supply. Disposal by incineration frequently brings the designer sharply around to the point from which he began. The combustion effluent itself may be an atmospheric nuisance comparable to that avoided by the gas-cleaning installation.

The mounting costs of safe disposal have had a profound effect upon the calculations that determine whether a waste removed from a gas should be converted to a low-grade raw material or by-product, or, instead, be carefully led through a maze of specialized treatment to prepare it for one of the few authorized destinations.

Disposal of Radioactive Wastes. By far the most exacting requirements for the disposal of wastes occur in the handling of radioactive materials discharged from atomic-energy processes. The separating element in an air or gas cleaner must be regarded as a concentrator of radioactivity, and accordingly its useful life may depend upon the measures taken for shielding the environment against the gradually accumulating level of radioactivity. This tends to minimize the storage space or holding capacity that must be provided at the point of separation.

Storage of waste may be permitted at isolated points, taking advantage of the spontaneous decay of radioactivity. In some cases burial or dumping at sea will be necessary.

XVII. Selection for Specific Requirements

Selection of the right air-cleaning system calls for an engineering compromise with a number of interacting factors, including the degree of cleaning required, initial and operating costs, equipment life, maintenance expense, and waste disposal. There is no formula that will combine these considerations, and thereby serve as a substitute for experience and good judgment. It is true, however, that economic considerations generally superimpose so much control over the selection of air-cleaning equipment that cost becomes the integrator of all other items in the analysis.

There is natural reluctance to accept the claims and guarantees of equipment manufacturers who have a limited selection of types from which to assemble a cleaning system. The fact remains, nevertheless, that reliable builders and installers of such equipment are in a better position to predict the abilities and limitations of their devices than are the customers.

It should be recognized that some applications must be approached honestly as experimental by both the supplier and the purchaser. However, when a guarantee is given, the purchaser should be on guard to see that performance is specified in terms that are truly significant, rather than in terms that merely sound impressive.

A. VERSATILITY

It is evident that equipment performance is highly dependent upon the heterogeneity of the air-borne matter. The versatility of a multistage system designed for removal of solid or liquid particles may be an important consideration in those applications where the size distribution is highly variable or fluctuating. The possibility of excessive changeability in the properties of the contaminated air may require some standby units of special abilities to provide for continuously high performance.

The versatility of water as a conditioning and separating liquid is partially responsible for its addition to many designs of air cleaners. It minimizes resuspension of separated solids and serves as a carrier medium for waste disposal. It dissolves many air-borne constituents and accommodates many liquid-phase reactions beneficial to high-degree separation.

The versatility of adsorbents for gases and vapors has made them attractive where the composition of the incoming gas is unpredictable. Thus, the versatility of active carbon has been recognized in air conditioning, odor control, gas-mask canisters, and ventilation of underground shelters.

B. INCOMPATIBILITIES OF AERODISPERSION AND EQUIPMENT

Some of the things that ruin a gas-cleaning installation may be classified as incompatibilities: some are destructive to performance, and some are destructive to life and property.

As an example of performance incompatibility: as gas velocity increases, long retention time is increasingly difficult to provide. Long retention time is desirable for diffusional processes, while high velocity is desirable for inertial processes. The two separating mechanisms are incompatible in the same zone of treatment, and accordingly must be compromised or segregated.

Hygroscopic solids are incompatible with dry fabric filtration without control of humidity of the carrier gas.

Metallic dusts, such as cast iron, that oxidize rapidly in the presence of moisture and air are incompatible with many kinds of washers or scrubbers using untreated water.

Oil or resin vapors that are condensable under the prevailing operating conditions are incompatible with some dry methods of filtration, as they quickly plug the medium and may prevent its regeneration or restoration to a tolerable pressure drop.

C. INCOMPATIBILITY OF LIQUID AGITATION AND SEDIMENTATION

In the operation of liquid systems of air cleaning there may be a need to clarify the liquid for recirculation to the separation or preparation zone. In many designs, this is done at the base of the treatment zone within the same enclosure.

There are in existence many examples of conflict between a high state of liquid agitation beneficial for gas and liquid contacting, and liquid stagnation, beneficial for dust particle sedimentation. That such mechanisms are incompatible in the same enclosure, of moderate dimensions, seems to have been overlooked repeatedly. The remedy is occupation of greater space, or the physical segregation of air-flow zones from sedimentation zones.

D. FIRE OR EXPLOSION HAZARDS

While it is possible to remove combustible materials from air without creating a fire hazard, failure to provide effective safeguards may lead to disaster. Following are some examples of dangerous conditions.

1. Separation of magnesium in water without sufficient capacity for dissipation of heat and purging of contact surfaces.
2. Filtration of metallic dust by means of cotton cloth, under conditions of operation that permit hot or incandescent particles to reach the fabric.
3. Electrostatic separation of constituents from combustible gas without adequate precaution to exclude air or oxygen.
4. Electrostatic separation of combustible dusts or mists from a gas containing oxygen without sufficient safeguards against spark discharge.
5. Adsorption of vapors in fluidized carbon without sufficient provisions for heat dissipation.

Any system handling combustible or explosive materials should be provided with multiple safeguards, including explosion relief panels or dampers. Automatic detectors and alarms for heat, fire, or smoke should be installed in a "fail-safe" manner.

E. COST ANALYSIS

A comprehensive cost analysis for air or gas cleaning will include most of the following items:

1. Noninstalled cost per unit air-flow capacity.
2. Installation cost including discharge stack.
3. Amortization based on known service life.
4. Fixed charges on space required by equipment.
5. Initial costs for disposal equipment.
6. Operating costs for disposal of wastes.
7. Preventive and corrective maintenance costs.
8. Scrubbing liquid costs.
9. Power or utility costs.
10. Recovery or salvage value of constituents.

Approximate information on the first item appears in Table 3. These data

TABLE 3

Cost of Air or Gas Cleaners[a]

(Dollars per 1000 c.f.m.)

Type of cleaner	Minimum noninstalled cost
Inertial separators	
Baffle chambers (gravity-inertial)	50
Cyclones (single, large diameter)	100
Cyclones (multiple, small diameter)	400
Fan-type (dry)	200
Filters	
Cloth baghouse (above 10,000 c.f.m.)	500
Reverse-jet cleaned (above 10,000 c.f.m.)	800
Unit air-supply ("throwaway")	10
Conveyorized impingement type	100
Active carbon (odor removal)	200
Electric precipitators	
Single-stage high-voltage (above 100,000 c.f.m.)	500
Two-stage low-voltage (air conditioning)	200
Scrubbers and washers	
Spray chambers	100
Cyclone scrubbers (stationary)	300
Mechanical or dynamic	500
Packed towers (chemical absorbers)	1000
"Disintegrator" scrubbers	3000

[a] Approximate minimum noninstalled costs, using ordinary steel construction; installed costs, complete with necessary auxiliaries, may be at least twice the figures given here; based on 1955 prices.

are given to indicate the wide range of costs encountered by the application engineer and to serve as a warning against hasty estimates. Even greater ranges of costs are experienced when the items mentioned above are included in the analysis.

F. POWER REQUIREMENTS

The energy consumed in cleaning air or gas is largely the power required to force the fluid through the system against the resistance of numerous obstructions placed in the stream to stop the air-borne matter. Table 4 presents the order of magnitude of pressure drop encountered with the several types of cleaning equipment. Along with pressure drop is given the estimate of power required, in kilowatts, to force 1000 cubic feet of air through the equipment in one minute against the specified resistance.

It is evident that no simple correlation exists between power consumption and separation ability for fine particles. However, for those mechanisms depending primarily on centrifugal force, the power requirement will rise as separation factor increases, resulting in more effective performance against the smallest particles.

TABLE 4

Power Requirements for Air-Cleaning Equipment

Equipment type	Pressure drop (in. H_2O)	Kilowatts required per 1000 c.f.m. air capacity[a]
Gravity settling chambers	0.05–0.2	0.02–0.1
Spray chambers	0.05–0.2	0.02–0.1
Electric precipitators	0.05–0.5	0.02–0.2
Impingement filters	0.5 –1	0.2 –0.5
Packed towers (wet)	0.5 –5	0.2 –2
"Absolute" filters	1–5	0.3 –2
Cloth arrestors	2–6	0.5 –2
Cyclone separators	1–5	0.3 –2
High-velocity centrifugals	3–15	1–5
Intensive scrubbers	2–30	1–10

[a] Does not include power to force air through duct system or to disintegrate scrubbing liquid by mechanical or hydraulic methods.

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CHAPTER X

Ventilation

W. N. WITHERIDGE

Ventilation is the process of passing clean air through any space, room, or building, with the object of diluting air-borne impurities to a safe or acceptable concentration or adjusting the heat and humidity in the environment. Contrary to popular belief, the control of oxygen and carbon dioxide for human respiration is not a major concern of ventilation, as will be shown later.

The term "ventilation" generally implies the improvement of chemical, physical, and esthetic properties of the inside atmosphere by introduction of outdoor air. However, we know now that in some highly industrialized areas outdoor air is less desirable than well-conditioned indoor air. In such places the simple process of replacing room air is not sufficient to produce an acceptable environment. This fact, together with the demand for conserving energy by air recirculation, has stimulated the development of highly effective air-cleaning devices. With these devices, ventilation is no longer limited to the use of outdoor air.

Contemporary air-conditioning processes fail in some degree to restore indoor air to its "unused" condition. For this reason, the air-conditioning engineer does not provide a completely self-contained or 100 per cent recirculating indoor atmosphere under normal circumstances. A submerged submarine is at present our nearest approach to a self-contained space for human occupancy, as it has at least a *safe* environment for respiration, entirely detached from the earth's atmosphere. Space flight will create a similar need for artificial air.

Many of us believe that outdoor air has some property, still undefined, that accounts for its "freshness" in contrast to indoor atmospheres, even after all known means have been utilized to remove every perceptible contaminant from the indoor air. Actually, the exhilarating effect of "country atmosphere" is the result of many kinds of stimuli, including sounds, odors, colors, distances, natural and man-made horizons, and complex variations in temperature, humidity, radiation, and air movement. Man has tried in many ways to duplicate the invigorating properties of outdoor air. His methods range through ozonation, ionization, ultraviolet radiation, perfuming, deodorizing, washing, and thermal adjustment. None of these experiments has solved the problem completely. Even so, the indoor atmosphere provided by the best current air-conditioning practice is quite satisfactory.

I. Human Ventilation Requirements

Ventilation of residential, commercial, and office spaces is now understood to be necessary to control body odors, tobacco smoke, cooking odors, and other odorous impurities, rather than to maintain the required amount of oxygen or remove the carbon dioxide produced by respiration. This is true because the standard construction of buildings for human occupancy cannot prevent the infiltration and exfiltration of substantial amounts of air, even when all window, door, roof, or mechanical-ventilation openings are closed. Published data[1] on the amounts of outdoor air normally available by natural ventilation or infiltration indicate that suffocation by deficiency of oxygen or excess of carbon dioxide, as a result of human respiration, is virtually impossible in buildings constructed above ground.

In view of the fact that industrial hygienists are called upon to justify this position to those who are not aware of the background of research and experience upon which present ventilation standards are based, a brief review of the effects of respiration on atmospheric air is in order at this point.

A. AIR COMPOSITION

The approximate composition of air under three conditions is given in Table 1. Simple calculations will demonstrate that human beings do not require more than a few hundred cubic feet of air per hour to satisfy their demand for oxygen and to dilute to a harmless concentration the carbon dioxide produced. A man, even at heavy work, breathes only about 40 liters (1.4 cu. ft.) of air per minute, consumes about two liters (0.07 cu. ft.) of oxygen, and produces about 1.7 liters (0.06 cu. ft.) of carbon dioxide.

TABLE 1
Composition of Air
(Volume per cent)

Component	Outdoor air, dry	Indoor air, 70° F. (RH 50)	Expired air, 97° F. (RH 100)
Inert gases (nitrogen, argon, etc.)	79.00	78.00	75
Oxygen	20.97	20.69	16
Water vapor	0.00	1.25	5
Carbon dioxide	0.03	0.06	4
Total	100.00	100.00	100

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[1] *Heating, Ventilating, Air Conditioning Guide, 1957*, American Society of Heating and Air-Conditioning Engineers, New York, 1957, ch. 11.

Mackey[2] offered an interesting hypothesis on the physical and chemical changes occurring in indoor air as a result of human occupancy. His analysis was somewhat as follows (modified after communication with Mackey):

> An adult at rest uses in one minute about 20 cubic inches of oxygen and produces about 18 cubic inches of carbon dioxide. At 70° F., he loses in one hour about 300 Btu of sensible heat and about 0.1 pound of water vapor. Assuming for simplicity that these rates remain constant (which they would not do in fact), if such an adult were confined in an airtight, thermally insulated space of 1000 cubic feet, initially at 70° F. (ignoring humidity), the dry-bulb temperature would increase to 100° F. in less than two hours, while about 75 hours would be required to reduce the oxygen to 16 per cent and increase the carbon dioxide to 5 per cent. "In this extreme case, the physical change is seen to be much more dangerous than the chemical."

B. CARBON DIOXIDE AS AN INDEX OF VENTILATION REQUIREMENTS

Measurement of carbon dioxide concentrations in spaces occupied by human beings had been standard procedure among ventilating engineers for many years until Yaglou, Riley, and Coggins[3] reported in 1936 their results from a series of experiments on ventilation requirements. They concluded that the carbon dioxide concentration "in the air of occupied rooms proved to be an unreliable index of ventilation, from the standpoint of both outdoor air supply and odor intensity" and suggested that "a great deal of unjustified effort would be saved by discontinuing the usual measurements of CO_2 in ordinary ventilation work, except perhaps in instances in which the air flow is well under 10 c.f.m. per person."

Many research workers and writers during the present century have recognized that existence of 0.10 to 0.50 per cent CO_2 in spaces occupied by human beings is not of itself dangerous. Some still express the belief, however, that such an increase in carbon dioxide, from a normal outdoor level of 0.03 to 0.04 per cent, indicates the presence of unhealthful constituents as a result of *vitiation of air* by human respiration. This question has not been settled to the satisfaction of the layman. The current use of odors as indexes of ventilation requirements is still suspected by some as neglect of a fundamental hazard to life and health. Nevertheless, public health workers and ventilation engineers are now generally convinced that oxygen and carbon dioxide concentrations in air at normal barometric pressures are not of concern to health in the absence of more substantial disturbances of air composition, as might be caused by industrial processes that consume oxygen or generate carbon dioxide.

The extended use of odor-controlling processes for air conditioning will bring about further revisions in the standards of quantities of outdoor air per capita specified for health or comfort.[4] In some situations it may be possible to approve a mechanical system of 100 per cent recirculation of indoor air, on the strength of the fact that sufficient outdoor air will find its way into the structure by natural forces. Certainly the advisability of operating an air-conditioning system without the use of outdoor air will depend upon future discoveries in the realm of air "freshness" and whether it proves possible to convince most persons that a synthetic environment is just as fresh and healthful as outdoor air.

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[2] C. O. Mackey, *Air Conditioning Principles.* International Textbook, Scranton, 1941.

[3] C. P. Yaglou, E. C. Riley, and D. I. Coggins, *Trans. ASHVE,* **42,** 133 (1936).

[4] C. P. McCord and W. N. Witheridge, *Odors: Physiology and Control.* McGraw-Hill, New York, 1949.

Ventilation rates for the control of tobacco smoke and body odors in various applications are suggested in Table 2.

TABLE 2

Recommended Quantities of Outdoor Air per Person[a]

Outdoor air (c.f.m./ person)	Type of space or occupancy
5–10	High-ceiling space such as: bank, auditorium, church, department store, theater; room with no smoking
10–15	Apartment, barber shop, beauty parlor, hotel room; room with light smoking
15–20	Cafeteria, drug store with lunch counter, general office, hospital room, public dining room, restaurant; room with moderate smoking
20–30	Broker's board room, private office, tavern; room with heavy smoking
30–60	Conference room, night club; crowded room with heavy smoking

[a]Air-cleaning or odor-removing devices not used. (Space not less than 150 cu. ft. per person' or floor area not less than 15 sq. ft. per person.)

State and city codes should be consulted to make certain that minimum outdoor-air requirements are followed.

C. EFFECT OF ROOM SIZE ON VENTILATION REQUIREMENTS

A series of experiments[3,5] on ventilation requirements for human occupancy demonstrated that

> air space per occupant in a room not only affects the disappearance rate of body odors and hence ventilation requirements, but also the efficiency of ventilation systems. Large rooms have an advantage over small ones, as they act like reservoirs, allowing body odors to disappear with a minimum supply of outdoor air and maximum ventilation efficiency. A small room would require a greater air supply per occupant for the control of body odor. An increased air supply entails a loss of ventilation efficiency, as the air passes quickly to the exhaust without removing a full share of odors, heat, and moisture.[5]

Table 3 summarizes the results of these experiments.

With respect to tobacco odors, however, their tendency to become more offensive during the first few hours after smoking indicated that retaining them longer in the occupied space by increasing the volume of the space actually was a handicap. The conclusion was that for control of tobacco smoke by dilution ventilation, small volumes of air space and high ventilation rates per capita would be a preferable combination.

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[5] C. P. Yaglou and W. N. Witheridge, *Trans. ASHVE*, **43**, 423 (1937).

TABLE 3

Requirements of Outdoor or Odor-Free Air for Dilution of Body Odors[3]

Air space (cu. ft./ person)	Clean air supply (c.f.m./person[a])	Type of occupants and kind of ventilating equipment[b]
100	29	School children; av. personal hygiene
100	25	Sedentary adults
100	22	School children; best personal hygiene
200	38	School children; poor personal hygiene
200	23	Laborers
200	21	School children; av. personal hygiene
200	18	School children; above av. personal hygiene
200	16	Sedentary adults
200	12	Sedentary adults; air washed by centrifugal atomizing humidifier
200	<4	Sedentary adults; summer season; air cooled and dehumidified by spray washer; water changed daily
300	17	School children
300	12	Sedentary adults
500	11	School children
500	7	Sedentary adults

[a] Based on impressions of persons entering experimental room from relatively clean air at "threshold" odor intensity. Allowable odor intensity of 2 on a scale ranging from 0 for no perceptible odor to 5 for nauseating or overpowering odor.

[b] Heating season, air not washed or conditioned, except as noted.

D. MINES, TUNNELS, AND UNDERGROUND SPACES

Man has burrowed underground for many years, and the deeper he goes, the more acutely conscious he becomes of excessively high temperatures and humidities and the presence of dangerous gases. The removal of industrial and residential quarters to underground air-raid shelters makes the ventilating and air-conditioning engineer a highly essential member of the design organization. Industrial hygienists are now generally aware that the conditioning of underground atmospheres is indispensable in the safe operation of deep mines.

The specialized problems of underground ventilation will not be discussed here. The reader is referred to comprehensive publications on this subject.[6]

II. General Ventilation

General ventilation may be classified in several ways to accommodate such distinctions as (*1*) natural or mechanical, (*2*) supply or exhaust, (*3*) directional or nondirectional, and (4) anemotive or gravity. Those groupings are actually abbreviated definitions of certain features of general ventilation.

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[6] G. E. McElroy, *U. S. Bur. Mines Bull.* No. **385,** 1935; D. Harrington and S. J. Davenport, Part 1, *U. S. Bur. Mines Circ.* No. **7001,** 1938, Part 2, *ibid.,* No. **7182,** 1941; D. Harrington, *Heating, Piping, Air Conditioning,* **17,** 275 (May, 1945); G. E. McElroy, A mine air-conditioning chart, *U. S. Bur. Mines Rept. Invest.* No. **4165,** 1947; I. M. Rice, Heating, ventilating, and air conditioning of underground installations, *Quart. Colo. School Mines,* **46,** 258 (January, 1951).

A. CLASSIFICATION OF GENERAL VENTILATION

1. *Natural General Ventilation*

Anemotive ventilation: air passing transversely through a space as a result of generally horizontal wind forces. The aeromotive forces also can be vertical as a result of suction produced on the roof of a building subjected to substantial wind velocity.

Thermal or gravity ventilation: air movement produced by vertical convection currents or indoor-outdoor temperature differences.

2. *Mechanical General Ventilation*

Nondirectional: (*1*) Supply, pressure, or plenum ventilation: air supplied to a space to create a *very slight* pressure, which forces air outward through any available opening, in the absence of wind pressure of greater magnitude. Distribution of the air supply must be fairly uniform to produce nondirectional general

TABLE 4

Air-Change Rates for General Ventilation

Type of room or building, public and industrial	Air changes/hour (Low–High)	Minutes/air change (Slow–Fast)
Auditoriums; assembly halls	4– 30	15– 2
Bakeries	10– 60	6– 1
Boiler rooms; engine rooms	4– 60	15– 1
Corridors; hallways; lobbies	1– 10	60– 6
Dairies; creameries	5– 30	12– 2
Foundries, ferrous	4– 30	15– 2
Foundries, nonferrous	6– 60	10– 1
Garages, storage and parking	3– 20	20– 3
Garages, repair	6– 30	10– 2
Hospitals, ordinary	2– 15	30– 4
Kitchens, commercial	10– 60	6– 1
Laboratories, chemical	6– 30	10– 2
Laundries; pressing shops	10–120	6–$^{1}/_{2}$
Locker rooms	2– 15	30– 4
Machine shops	3– 20	20– 3
Offices, general and private	2– 30	30– 2
Restaurants; cafeterias	4– 30	15– 2
Residences (excluding kitchen)	1– 6	60–10
Retail stores	6– 20	10– 3
Smoking rooms; lodge rooms	10– 60	6– 1
Toilets; bathrooms	10– 30	6– 2
Waiting rooms; lounges	3– 10	20– 6
Warehouses	1– 6	60–10

ventilation. (*2*) Exhaust, suction, or vacuum ventilation: air removed from a space to create a *very slight* reduction in pressure, which causes outdoor air to force its way in through any available opening.

Directional: (*1*) Localized dilution by air supply; also termed "forced dilution" and "forced diffusion": clean air is *blown* across the work area toward the source of contamination to diffuse a contaminant into the large air reservoir of the room. The principal objections to this method are the dangers of creating excessive drafts on workers and of blowing contaminants through the workers' breathing zone. (*2*) Localized dilution by air exhaust: clean air is *exhausted* across the work area toward the source of contamination, but no exhaust hood or process enclosure is provided. This method of ventilation exemplifies the close relation between general and local ventilation; it is essentially the same as moving a process close to a wall-type exhaust fan to take advantage of the gradually increasing velocity as the air approaches the fan.

B. GENERAL VENTILATION SPECIFICATIONS

There are in current use the following methods of specifying general or space ventilation rates: (*1*) air changes per hour (Table 4); (*2*) minutes per air change (Table 4); (*3*) air flow per square foot of floor (Table 5); (*4*) air volume on a per capita basis (Table 2); (*5*) air volume required to dilute known or predictable concentrations of air contaminants to safe or acceptable levels.

The following example illustrates the interrelationships between the first four methods of specifying space ventilation:

Assume a classroom with the following dimensions:

10 ft. ceiling
15 sq. ft. of floor area per person
150 cu. ft. of air space per person

The following ventilation rates are identical for this room:

30 c.f.m. per person
2 c.f.m. per square foot of floor area (30/15)
5 minutes per air change (150/30) or (10/2)
12 air changes per hour (60/5)
120 c.f.h. per square foot of floor (12 × 10) or (2 × 60)
1800 c.f.h. per person (12 × 150) or (120 × 15) or (30 × 60)

1. General Ventilation Rates in Terms of Air Changes

The amount of ventilation for a room or building is commonly expressed as the number of times per hour that a complete change of air is effected, or as the number of minutes required to produce one complete change of air. The mathematics of the air-change method of estimating ventilation assumes that air distribution is uniform throughout the room or building. In practice, such ideal distribution is seldom, if ever, accomplished. Furthermore, the dilution of contaminants is a gradual process and, even after the contaminating operation is discontinued, it may take hours to clear the space by general ventilation.

The wide range of values in Table 4 makes it evident that a good deal of judgment is necessary in selecting the proper rates of air change. Experienced designers usually check ventilation estimates by at least two methods of computation, if alternate data are available. General ventilation requirements should not be estimated in terms of air changes if harmful, irritating, offensive, or flammable air contaminants are dispersed by activities within the occupied space. In such cases the required ventilation is the amount needed to dilute the estimated or measured air contamination down to a permissible concentration. However, control by dilution may not be the best solution; local exhaust ventilation is advisable when the types and concentrations of air contaminants from a process vary considerably from time to time.

2. General Ventilation Rates Based on Floor Area

When the specific equipment or per capita requirements are not known, it is convenient to estimate ventilation on the basis of the amount of floor area devoted to known kinds of activity. Of course, a continuously changing factory layout may be difficult to appraise for ventilation requirements. However, one important advantage in this method of specifying ventilation is that air-flow rates are independent of ceiling heights. The air-change method, on the contrary, penalizes the

TABLE 5

General or Space Ventilation Rates Based on Floor Area

Ventilation/sq. ft. of floor		
c.f.m.	c.f.h.[a]	Type of room, building, or process
1	60	General industrial buildings having no localized sources of unhealthful, irritating, flammable, or explosive air contaminants
1	60	Storage garages mechanically ventilated (either supplied or exhausted air)
1.5	90	Gymnasiums; dance halls
3	180	Bath and toilet rooms
2	120	Battery charging rooms
3	180	Small repair garages
1.5	90	Large dining rooms
2	120	Small dining rooms
2	120	Spacious kitchens
4	240	Average restaurant kitchens
10	600	Small congested kitchens
50	3000	Enclosures or booths for arc welding
100	6000	Rooms for abrasive blasting or metal spraying (supplied-air helmets required for workers)

[a] c.f.h. ÷ actual or assumed height = air changes per hour.

designer who provides an extra-high ceiling because it requires greater quantities of air to comply with some predetermined air-change figure based only on the type of industry. Actually, high ceilings in industrial buildings reduce rather than increase the required mechanical-ventilation rate, so far as the ground-floor-level working zone is concerned.

Table 5 gives a few examples of values used with this method of estimating ventilation.

3. Dilution Ventilation (General and Local)

If enough clean air is mixed with contaminated air, the concentration of the contaminant may be diluted to any reasonable level. It is obviously an advantage to know both the initial and desired concentrations and the efficiency of diffusion if the requirements of this method are to be predicted successfully. The application of dilution ventilation has been largely experimental, empirical, or trial-and-error, on the basis of visual or sensory observations of the *before and after* levels of contamination.

A simple formula is available for computing the required amounts of clean air for dilution purposes when the quantities of air contaminant produced and the concentration that may be permitted in the human environment are known or are capable of estimate:

$$AC = \frac{\text{contaminant released (c.f.m.)}}{\text{dilution air required (c.f.m.)}}$$

where AC = allowable concentration of contaminant in volumetric units, and c.f.m. = cubic feet per minute.

The above formula requires that the *allowable concentration* be expressed in parts of contaminant per million parts of air, and indicates that the p.p.m. figures in common use by industrial hygienists can be used directly in dilution-ventilation specifications by translating "parts per million" into the expression "cubic feet of contaminating gas or vapor per million cubic feet of air." Therefore, if it is estimated that an internal combustion engine produces 60 c.f.h. of carbon monoxide or 1 c.f.m. CO, and the allowable concentration is 100 p.p.m. CO:

$$AC = 100 \text{ p.p.m.} = \frac{100}{1{,}000{,}000} = \frac{1\,(\text{c.f.m. CO})}{x\,(\text{c.f.m. air})}$$

where x = 10,000 c.f.m. air to maintain 100 p.p.m. CO.

If the allowable concentration is expressed in gravimetric units, the amount of contaminant produced should be estimated correspondingly on the weight basis so that a simple dilution formula can be used for computing general ventilation. For example, assume that an arc welding operation generates 1000 mg. of fume per minute and that a fume concentration of 10 mg. per cubic meter of air is permissible:

$$AC = \frac{10 \text{ mg.}}{\text{cu. m.}} = \frac{1000 \text{ (mg. fume per minute)}}{x \text{(cu. m. of air per minute)}}$$

where x = 100 cu. m. of air per minute, or 3500 c.f.m. to maintain a fume limit of 10 mg. per cubic meter (using a rounded figure of 35 cu. ft. per cubic meter).

It is important to observe that any mathematical expression, as outlined above, assumes 100 per cent uniformity and thoroughness of mixing of contaminant with air. Obviously a correction must be applied to such a theoretical result, and at this point the designer's experience and judgment must enter. In general, it is recommended that dilution efficiency be anticipated in the range of 25 to 50 per cent, which means that 2 to 4 times the theoretical air volumes should be provided in the capacity of the actual installation. If the worker is near the source of air contaminants, this method of computation should be used only for estimating the order of magnitude of local exhaust ventilation required. Used in this manner, it serves as a check on the ventilation rates determined from minimum controlling air velocities and maximum areas through which the contaminant may escape.

TABLE 6

Dilution Ventilation Requirements for the Control of Solvent Vapors[a]

		Requirements for Health		Requirements for Fire Prevention	
Liquid	Vapor (cu. ft./pt. liquid at 70° F.)	Allowable concentration for human exposure 8 hr./day (p.p.m.)[b]	Air (cu. ft./pt. liquid evaporated, nearest 1000)	Allowable concentration for fire safety $^1/_5$ lower explosive limit (p.p.m.)[b]	Air (cu. ft./pt. liquid evaporated, nearest 100)
Acetone	5.5	500	11,000	5,100	1,100
Amyl acetate	2.7	200	14,000	2,200	1,200
Benzene	4.6	100	46,000	2,700	1,700
Butyl acetate	3.1	200	16,000	2,800	1,100
Carbon disulfide	6.7	20	335,000	2,500	2,700
Carbon tetrachloride	4.2	50	84,000		
Diethyl ether	3.9	500	8,000	3,700	1,100
Ethyl acetate	4.1	200	21,000	4,400	900
Ethylene dichloride	5.1	100	51,000	12,400	400
Gasoline	3.0	500	6,000	2,800	1,100
Methyl alcohol	10.1	200	50,000	13,400	800
Toluene	3.8	200	19,000	2,500	1,500
Trichloroethylene	4.5	200	23,000		
Turpentine	2.6	200	13,000	1,600	1,600
Xylene	3.3	200	17,000	2,000	1,700

[a] Air volumes are based on quantities of solvent evaporating into the workroom. Quantities of air required per minute or per hour must be determined by estimating the solvent losses in pints per minute or per hour.

[b] p.p.m. = parts of vapor per million parts of air; 1 per cent equals 10,000 p.p.m.

4. Dilution Ventilation for Control of Solvent Vapors

Dilution ventilation is occasionally the only practical method of controlling solvent vapors arising from industrial operations covering large areas of a plant. Ventilation requirements are based on the volumes of air needed to dilute the vapor to a safe or satisfactory concentration.

Table 6 indicates the large differences between the dilution air volumes required for fire prevention and those required for the prevention of illness or occupational disease. The required volumes of air stated in this table would apply only if completely uniform distribution of air supply were possible. Furthermore, it is assumed that vapors are *released uniformly* throughout the room. Inasmuch as neither of these conditions is probable, and since workers are usually rather near the evaporating solvent, it is therefore recommended that the designer provide at least twice the amounts of air given in Table 6.

5 Vapor Equivalents of Liquids or Solvents

The amount of pure vapor formed at sea level by the evaporation of a known volume or weight of liquid can be calculated by one of the following formulas:

$$\text{(A)}\quad \frac{\text{cubic feet of vapor}}{\text{pound of liquid}} = \frac{(\text{liters per mole})\,(\text{grams per pound})}{(\text{liters per cubic foot})\,(\text{grams per mole})}$$

$$\text{(B)}\quad \frac{\text{cubic feet}}{\text{pound}}\ \text{at } 0^\circ\ \text{C.} = \frac{(22.41)\,(453.6)}{(28.32)\,(\text{mol. wt.})} = \frac{359}{\text{mol. wt.}}$$

$$\text{(C)}\quad \frac{\text{cubic feet}}{\text{pound}}\ \text{at } 70^\circ\ \text{F.} = \frac{(530)\ (359)}{(492)\,(\text{mol. wt.})} = \frac{387}{\text{mol. wt.}}$$

$$\text{(D)}\quad \frac{\text{cubic feet}}{\text{pint}}\ \text{at } 70^\circ\ \text{F.} = \frac{(387)\ (1.041)\ (\text{sp. gr.})}{\text{mol. wt.}} = \frac{403\ (\text{sp. gr.})}{\text{mol. wt.}}$$

$$\text{(E)}\quad \frac{\text{cubic feet}}{\text{pint}}\ \text{at } 25^\circ\ \text{C.} = \frac{(537)\,(403)\,(\text{sp. gr.})}{(530)\,(\text{mol. wt.})} = \frac{408\ (\text{sp. gr.})}{\text{mol. wt.}}$$

1.041 in equation (D) is pounds of water per pint at 70° F.
22.41 in equation (B) is liters per mole at 0° C.
28.32 in equation (B) is liters per cubic foot
453.6 in equation (B) is grams per pound
492 in equation (C) is 0° C. in Fahrenheit degrees absolute
530 in equation (C) and (E) is 70° F. in degrees absolute
537 in equation (E) is 25° C. in Fahrenheit degrees absolute

For ventilation estimates, a constant of 400 in equation (C) is quite satisfactory. Equation (D) or (E) may be combined with the allowable concentration on page 294 to simplify the determination of ventilation required for adequate dilution. In the following equation, allowable concentration must be in parts of vapor per million parts of air:

$$\frac{\text{cubic feet of air}}{\text{pint of liquid}} = \frac{400{,}000{,}000 \text{ (specific gravity of liquid)}}{\text{(allowable concentration) (molecular weight)}}$$

Thus, if the designer is given an allowable concentration for trichloroethylene of 100 p.p.m., the dilution ventilation for 100 per cent efficient distribution would be:

$$\frac{\text{cubic feet}}{\text{pint}} = \frac{(400{,}000{,}000)\ (1.5)}{(100)\ (131)} = 45{,}000 \text{ (approx.)}$$

C. DISPERSION OF AIR CONTAMINANTS BY GENERAL VENTILATION

One of the important disadvantages of general ventilation is that it permits the building or room to become a large settling chamber for any dusts, fumes, or mists suspended in the air, even though the concentration may be within acceptable limits so far as health and safety are concerned. This has been most dramatically demonstrated in plants manufacturing or using highly combustible dusts. Although the dust concentrations at any one time were not sufficient to constitute a nuisance or hazard, the accumulation over many months or years has resulted in disastrous explosions of dust that had been deposited on rafters and inaccessible machinery surfaces.

In some cases the settling or separation of contaminants from the air may represent condensation of materials, vaporized by high-temperature processes, which may accumulate on all surfaces with ever increasing danger. Serious flash fires have occurred where the interior surfaces of the building were well impregnated or saturated with condensed vapors of flammable liquids or waxes. Even in our homes, laboratory tests have shown "that some of the fish fried on the stove is likely to condense on an upstairs window pane in a matter of seconds."[7]

D. AIR-SUPPLY INLETS AND EXHAUST OUTLETS

The design of ventilating equipment for an industrial plant is not complete without full consideration of the routes by which air will enter and leave the working areas. In fact, the ventilation route is important not only to the occupants of the building, but also to the neighbors and community at large. The demand for better inside conditions may result in the transfer of contaminants from the inside to the outside, in the absence of air-cleaning equipment. Although the outdoor air has a tremendous ultimate capacity for absorbing air contaminants, the dilution process is by no means immediate, as those who are near some industrial plants will verify.

[7] G. Nelson and H. Wright, *Tomorrow's House*, Simon and Schuster, New York, 1945.

The location of air inlets and outlets has the following significant aspects:

*1. Air Inlets**

(*a*) Sufficient combined or total inlet area should be planned to accommodate the required volume of make-up air during the heating or cooling season, whichever needs the larger volume. This will prevent excessive inlet velocities that consume power, create drafts on workers, stir up dust, and interfere with local exhaust hoods. The chosen inlet velocity is likely to be an engineering compromise between low rates, which require large inlet areas, and high rates, which facilitate rapid dilution of contaminants.

(*b*) If widespread hazardous operations are controlled by dilution or general ventilation, inlets should be well distributed around the building to provide uniform circulation.

(*c*) If contaminants are controlled by *localized dilution,* or by forcefully diffusing them into the general room-air reservoir, inlets may be purposely located to give nonuniform air-supply distribution.

(*d*) Inlets should be located to take full advantage of any thermal or convection effects within the building. For this purpose the designer must avoid the location of inlets (and outlets) near the "neutral zone"[8] of inside-outside pressure differentials, which is approximately midway between the floor and roof.

(*e*) Inlets should be located remote from stacks or ventilators discharging contaminants from the same or neighboring structures.

2. Air Outlets

(*a*) Outlets should be located as far as possible from air inlets to prevent "short-circuiting." This advice should be followed for both natural and mechanical ventilation.

(*b*) As in the case of air inlets, if widely scattered operations are controlled by general dilution, outlets should be uniformly distributed around the building (see 1*b* above).

(*c*) As in the case of air inlets, if contaminants are controlled by localized dilution, air outlets may be purposely located to short-circuit a corner of a large room in order to create a high rate of air change there without involving the atmosphere of the entire space. This method of localized space ventilation requires a higher rate of exhaust air than supply air within the area to be controlled, so as to prevent the spread of contaminants throughout the room (see 1*c*).

(*d*) Outlets should be placed to take full advantage of thermal effects (see 1*d*).

---

* The distinction between inlets and outlets is based on point of view; in this discussion, the point of reference is the occupied space, and not the interior of air ducts.

[8] J. E. Emswiler, *Trans. ASHVE,* **32,** 59 (1926).

(e) Outlets should be protected against the direct force of prevailing winds, which reduce the capacity of exhaust fans when provided, or which destroy the anticipated air-flow route planned on the basis of thermal effects inside the building.

E. SHORT-CIRCUITING THE AIR SUPPLY

"Short-circuiting" usually implies that outdoor air is allowed to enter and leave a room by such a short route that it contributes very little to the air circulation and the dilution of impurities. This may occur with either natural or mechanical ventilation.

Short-circuiting is not, however, an invariable handicap. While short-circuited air escapes without conveying its share of general contamination, it likewise helps to conserve heat in the wintertime since it removes less heat than well-diffused air. If outdoor air can be short-circuited directly to an exhausted process without coming in direct contact with workers, substantial heat saving may be realized.

One designer, on observing that a large exhaust system was creating an air-bound room, decided to short-circuit the outdoor air directly to a large number of ventilated tanks, instead of passing it through the entire space between the building walls and the processing area. The cold air was brought in through vertical ducts located a few inches above each tank and it traveled horizontally to slot-type exhaust hoods. The low temperature of the air actually proved to be an advantage in holding it down near the tank surface, and since it did not pass through the working zone, no one was subjected to cold drafts.

F. PROGRESSIVE VENTILATION

A useful concept in the interest of air-handling economy is "progressive ventilation." The air removed from an industrial plant frequently may be directed in a way that will provide both local and general ventilation. In fact, the air may be routed through several areas in succession, always in the direction of increasing air contamination, so long as the exhaust from one area is acceptable as the supply for the next area. The objective and result of progressive ventilation are the saving of air-borne heat and air horsepower.

The following examples of progressive ventilation will serve to suggest other applications:

Air from such areas as:	May be used to ventilate:
Corridors or hallways	Offices
Offices	Manufacturing areas
Manufacturing areas	Washrooms, toilet rooms
General manufacturing	Local exhausted areas
Theater auditoriums	Projection rooms
Gymnasiums	Bathrooms, lavatories
Schoolrooms, classrooms	Cloakrooms, locker rooms
Dining rooms	Kitchens
Locker rooms	Toilet rooms

G. GENERAL VENTILATION VS. LOCAL EXHAUST VENTILATION

The art of industrial process ventilation has been somewhat evolutionary from the natural general ventilation achieved by correct design of industrial buildings for hot, humid, and dusty operations to the highly effective local exhaust hoods in current use. Local ventilation prevents the spread of air contaminants throughout the building atmosphere with surprisingly small quantities of air flow in comparison with the volumes of air required by general ventilating systems. In spite of this characteristic air conservation of local ventilation, there are highly persuasive reasons why general ventilation still is selected by many industrial managements: (*1*) simplicity and economy of natural general ventilation, (*2*) relatively low first cost of mechanical general ventilation, (*3*) absence of interference with manufacturing operations, (*4*) flexibility in plants with constantly changing layouts, (*5*) existence of contaminating processes throughout the entire plant, (*6*) desire for large volumes of air circulation in hot weather, (*7*) discovery that local exhaust systems do not eliminate the necessity of supplying large volumes of heated air in the wintertime to replace that escaping from loosely constructed buildings by exfiltration. This volume of air change may be more than ample to control process air contaminants by the method of dilution, if means are provided to disperse contaminants from the immediate vicinity of the workers.

III. Industrial Process Ventilation

There can be no well-drawn line between general and local ventilation as applied to industrial processes because even with only local exhaust provided, the result is some degree of general ventilation in the boundary zone between the room and the process. Local and general ventilation are somewhat analogous to local and general illumination, which must be integrated for the highest visual efficiency.

In many plants the quantity of air handled by a local exhaust system is entirely adequate to provide simultaneous general ventilation for other parts of the plant. Air-intake openings can be placed so that air reaching the local exhaust hood passes over the largest possible surrounding area, thereby doing its full share of *general* ventilation. On the other hand, if a "short circuit" is allowed to exist between the exhaust hood and a nearby window or roof ventilator, some parts of the work space may receive no air circulation whatever.

A. INDUSTRIAL PROCESS ENCLOSURES

One serious disadvantage of general ventilation is the impossibility of recovering all the contaminant once it has escaped into the room atmosphere. Control is chiefly a matter of diluting the transient dusts or gases to a permissible concentration. The logical solution is to find some way to confine the contaminated air. In the event that a compact local exhaust hood around or close to the process is not feasible, the most suitable compromise is to enclose the entire process in a specially designed room.

The enclosure of a process to enable more satisfactory control of its atmospheric environment differs from general ventilation in the following two features. (*1*) The concentration of contaminant within the room or booth may be several times the allowable exposure, and workers inside would then be required to wear respiratory protective devices to supplement the ventilation. (*2*) The room or booth may be designed so that workers can perform their tasks from the outside or at the face of an opening. In this case the dust, mist, or fume concentration inside the booth is of no concern to the health of workers. Fire hazard, process visibility, or product quality may then determine the standard of adequate ventilation.

1. Paint-Spray Rooms or Booths

Paint-spray rooms that are open on one side are known as spray *booths*. Booths large enough for men to work inside, with or without respiratory protection, may be classed as a form of general ventilation, while those designed so that operators work outside might be rated as local exhaust hoods. Booths represent a transition between general and local ventilation; some classifications give them separate status, for convenience.

Clean air is drawn into the spray booth and across the worker's breathing zone. The usual method of specifying ventilation for spray booths is to state the velocity of air movement into the open face or side. Fifty linear feet per minute is very low velocity, suitable only for very large room-size booths, while 400 l.f.m. would be considered unnecessarily high for most jobs. The most widely accepted figure for small booths is 200 l.f.m. "face velocity" or 200 c.f.m. of air per square foot of face opening. Large booths operate satisfactorily on 100 l.f.m. for paints of low hazard, probably because the large mass of air moving toward the booth opening will control by dilution any escaping contamination.

2. Welding Booths or Rooms

Booths or rooms for welding vary from small square canvas enclosures, with rapid air change, to large permanent rooms. Quite often the booth will contain a local exhaust hood or downdraft ventilated bench. Ventilation requirements have been estimated in many ways, including: (*a*) c.f.m. based on size and kind of welding rods used; (*b*) c.f.m. based on weight of rod burned per minute; (*c*) c.f.m. based on power consumption at the arc; (*d*) optimum air velocity through a grille-top bench; (*e*) minimum air velocity into a "spot exhaust" hood at a specified distance from the arc; and (*f*) desirable air movement past the worker's head. The use of so many estimating procedures shows that requirements cannot be standardized. The best approach is to figure the ventilation rates by several methods to establish reasonable agreement in the selection of air-flow constants.

A convenient rule of thumb for checking the amount of ventilation provided in welding booths or rooms is based on the rate of electrode burning. For coated steel rods, the ventilation rate to keep the fume concentration down to 10 or 15 mg. per cubic meter of air may be estimated by the formula:

$$\text{c.f.m.} = \frac{100{,}000\ (\text{electrode diameter, inches})^2}{\text{minutes per electrode}}$$

If welding is continuous by several persons simultaneously, the *minutes per electrode* in this formula include the idle time both during welding and during the exchange of electrodes. If welding is intermittent by one person, the *minutes per electrode* should be only the elapsed time to burn one full electrode; the ventilating fan may be turned off if welding is idle for extended periods. (See also section on dilution ventilation.)

3. Abrasive-Blasting Rooms

These are complete enclosures for sand blasting, shot blasting, grit blasting, or hydroblasting. The concentrations of dust or mist in these rooms are enormous, and special supplied-air helmets must be provided for the workers. Preferably, complete protective suits are used because of the destructive effect of flying abrasive. Ventilation requirements are estimated either in (*a*) air changes per minute, (*b*) c.f.m. per square foot of floor area, or (*c*) c.f.m. per blasting nozzle in operation. Method (*c*) is used when the ventilation rates of similar blasting operations conducted in rooms of greatly different volumes are being compared. It is also a more rational method of relating ventilation to the amount of dust produced when the number of blasting operators in a given room varies. The ranges of ventilation rates used with these three methods of specification are: (*a*) 5–15 air changes per *minute;* (*b*) 50–150 c.f.m. per square foot of floor; and (*c*) 5,000–15,000 c.f.m. per nozzle in use.

4. Metalizing or Metal-Spraying Rooms

These may be similar to abrasive-blasting rooms, and the required personal protective equipment likewise similar, but without the necessity of protection against high-velocity abrasive particles. Spraying of metallic lead within a room results in a tremendous potential hazard, and the best possible supplied-air respirator is necessary even though the ventilation may be excellent. Spraying of steel also creates a high concentration of particulate matter, but it is possible to design ventilating equipment that can prevent dangerously high air-borne concentrations. Even so, the nuisance may not be tolerable, and some form of filter respirator might be required.

5. Grinding Booths

Booths for portable grinding processes have proved their practicability, and for many reasons of convenience and maintenance, seem to be superior to local

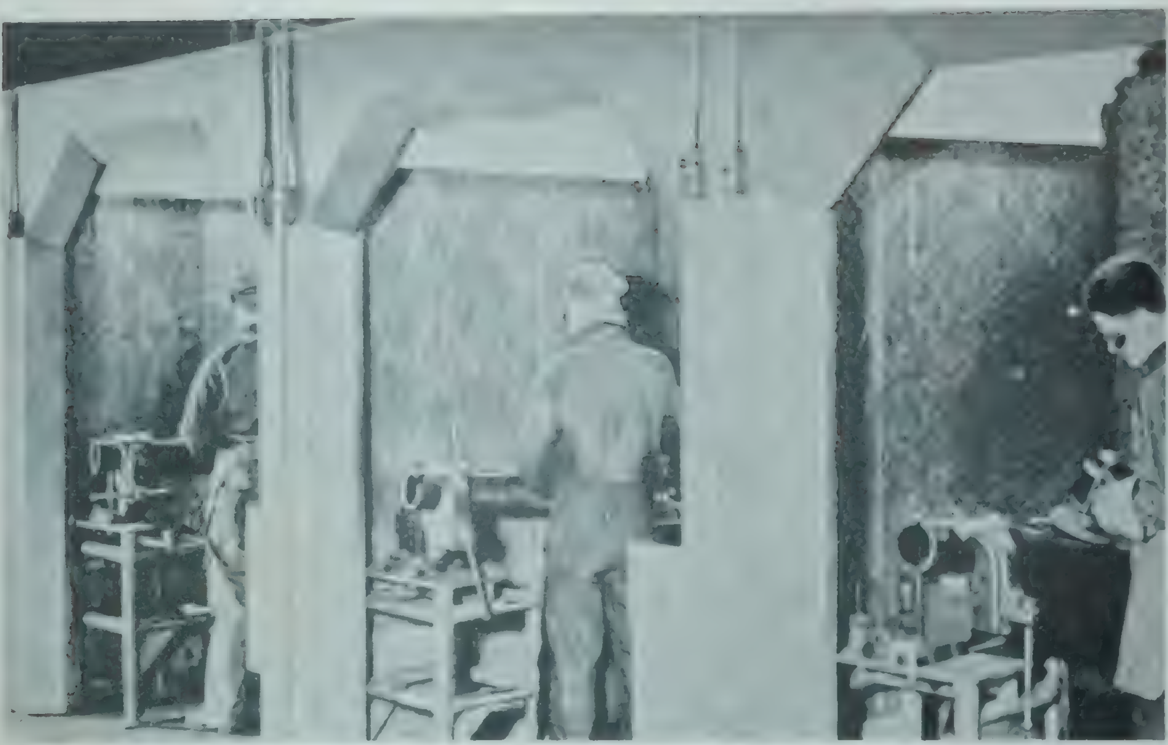

Figure 1. Booth-type enclosure for portable grinding—worker inside. (Courtesy American Air Filter Co., Louisville.)

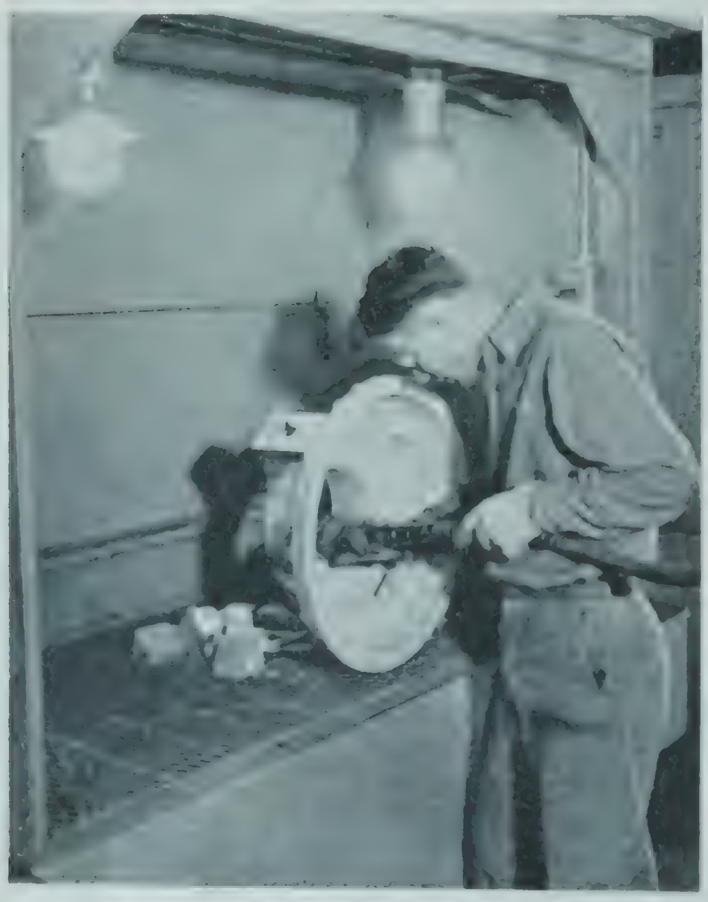

Figure 2. Booth for grinding magnesium castings combined with wet dust collector. (Courtesy Peters-Dalton, Inc., Detroit.)

exhaust hoods for snag-grinding wheels. Face velocities into grinding booths should prevent the escape of dusty air, but need not hold the large particles in suspension. Velocities of 100 to 300 l.f.m. are good practice. Figures 1 and 2 illustrate two methods of applying booths, where the operator may be either inside or at the face of the process enclosure.

6. Casting Shakeout Enclosures

Figure 3 is a shakeout process enclosure closely related to the canopy-type hood, modified only by dropping the edges down around the operation to confine the air contaminant and reduce the required ventilation rate.

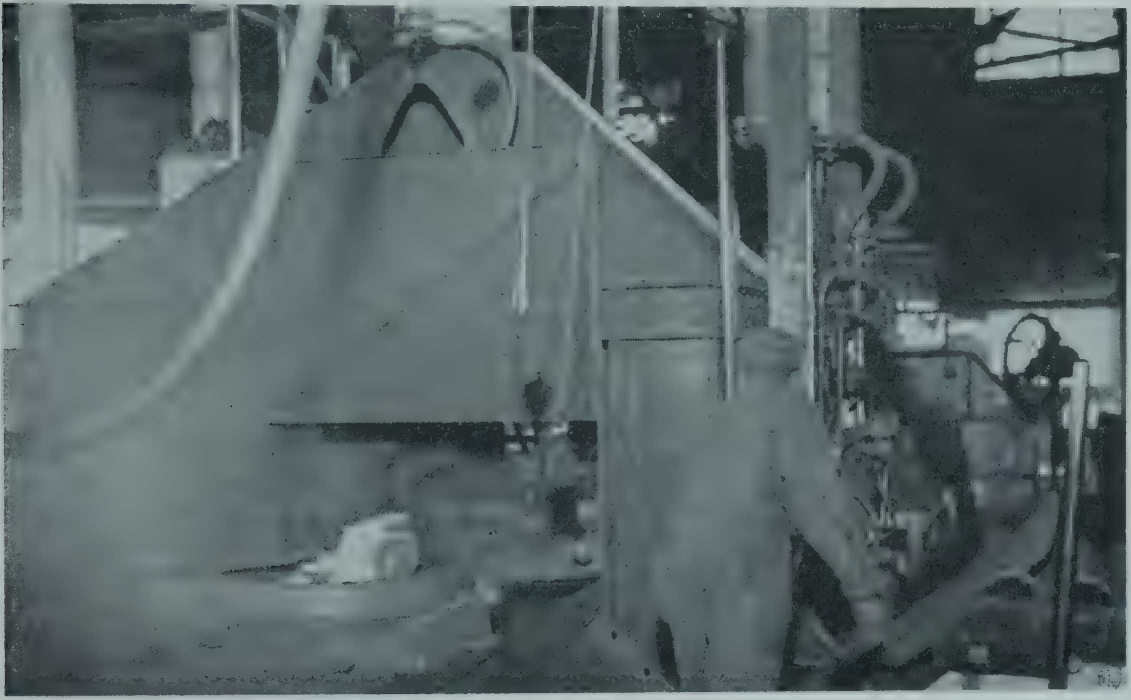

Figure 3. Exhausted enclosure for car-wheel casting shakeout. (Courtesy Claude B. Schneible Co., Detroit.)

B. LOCAL EXHAUST VENTILATION

The air volume requirements for the control of air contaminants by general ventilation are many times greater than the volumes required with carefully designed local exhaust hoods. For this reason a word of caution is advisable before the characteristics of exhaust hoods are reviewed in detail.

Exhaust hoods occasionally cannot be used as originally intended by the designer; whereupon the factory operating personnel is inclined to modify the strategy of ventilation. In consequence, if an exhaust hood becomes nothing more than a device for creating general ventilation in the vicinity of a process conducted most of the time *beyond the effective range of the hood*, the designer's original estimate of required air-flow rates cannot apply. Furthermore, it would not be economical to increase the air-flow rate through such a local exhaust hood to bring it up to general ventilation volumes because the suction power requirements would be exorbitant. General ventilation should be provided by low-velocity, low-suction equipment. The warning, then, is *not to overestimate the capability of an exhaust hood as a general ventilating device.* Special systems of multiple hoods operating simultaneously in small rooms have been observed in some cases to give high rates of air change for the space. This condition is not a property of exhaust hoods, but instead the result of greatly reduced air space per hood.

1. Exhausting vs. Blowing

Figure 4 illustrates the fundamental difference between blowing and exhausting devices. Air blown from a small opening retains its directional effect for a considerable distance beyond the plane of the opening. However, if the flow of air is reversed so that the same opening (or its equivalent in size) now handles the same volume of air by exhaust, the flow becomes almost completely nondirectional and its range of influence is greatly reduced. It is for this reason that local exhaust hoods should not be contemplated for any process that cannot be conducted in the immediate vicinity of the hood.

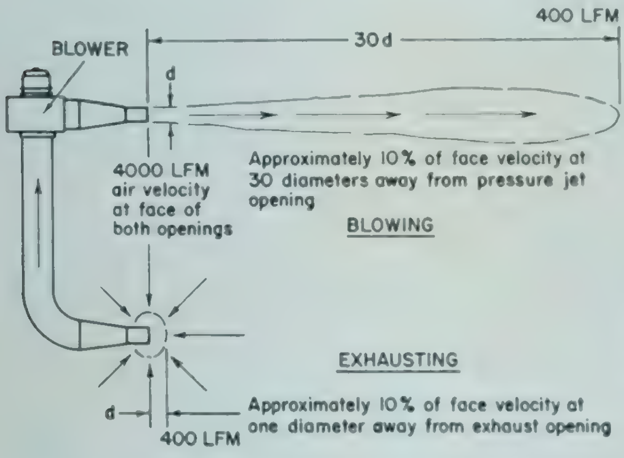
BLOWER
30d
400 LFM
d
4000 LFM air velocity at face of both openings
Approximately 10% of face velocity at 30 diameters away from pressure jet opening
BLOWING
EXHAUSTING
Approximately 10% of face velocity at one diameter away from exhaust opening
d
400 LFM

Figure 4. Air-flow characteristics of exhausting and blowing devices.

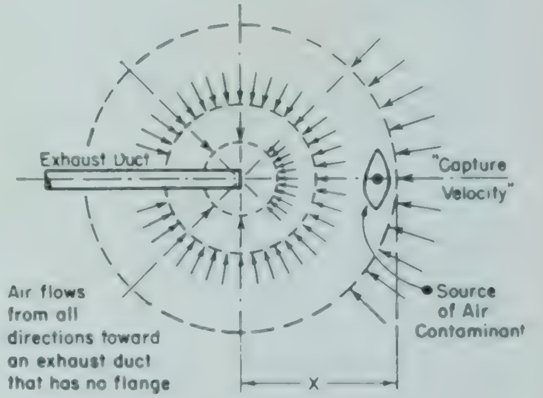
Exhaust Duct
"Capture Velocity"
Source of Air Contaminant
Air flows from all directions toward an exhaust duct that has no flange
X

Figure 5. Spherical nature of air flow into an unflanged and unobstructed exhaust hood.

2. DallaValle's Equation for Unobstructed Hoods

This equation is used to determine the relation between the quantity of air flowing into an exhaust hood and the resulting air velocity at a distant point along the hood centerline. The equation applies only when there is no obstruction between the hood opening and the control point in question (see Figure 5).

A simplified form of the equation for both round and rectangular hood openings is as follows:

$$Q = V\left(\frac{X^2}{b} + A\right)$$

where A = area of hood opening in square feet, b = a constant that depends upon the shape of the hood, Q = quantity of air flow in c.f.m., V = centerline air velocity in l.f.m. at X feet from opening, and X = distance in feet from hood opening to control point.

DallaValle's equation is used frequently with a value of 0.1 for constant b, giving a simple approximate formula suitable for round or essentially square hoods. With this constant the equation is given in the convenient form: $Q = V(10X^2 + \mathrm{A})$. Table 7 lists the constants and equations for hood openings of various proportions.

3. *Flanges and Baffles Increase the Range of Exhaust Hoods*

Figure 6 illustrates the beneficial effect of restricting the direction of air flow into an exhaust opening. The diagrams were constructed on the basis of a point source of exhaust which, of course, does not occur in practice. Figure 7 shows the true velocity contours and streamlines for a rectangular hood and indicates the marked deviation from spherical contours at points close to the hood face.[9] Figure 8 illustrates a flanged "spot exhaust" hood for arc welding.

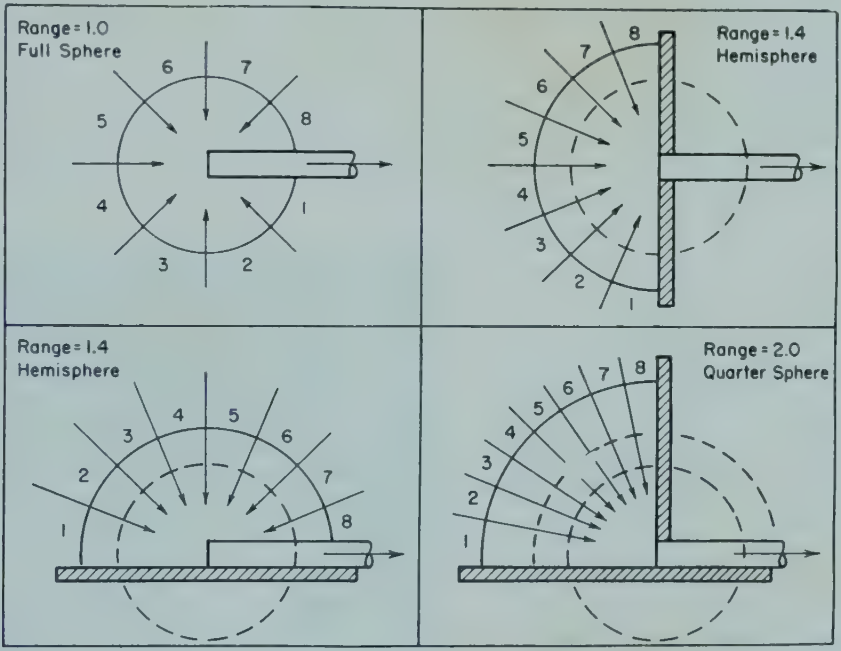

Figure 6. Flanges and baffles increase the range of exhaust openings.

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[9] J. M. DallaValle, *Exhaust Hoods*. Industrial Press, New York, 1944.

TABLE 7

DallaValle's Equation for Various Forms of Exhaust Hoods[9]

Shape of hood opening	Constant b	Equation
Circular	0.083	$Q = V(12X^2 + A)$
Square	0.083	$Q = V(12X^2 + A)$
Rectangular, sides in following proportions:		
10 × 9	0.081	$Q = V(12X^2 + A)$
10 × 8	0.078	$Q = V(13X^2 + A)$
10 × 7	0.075	$Q = V(13X^2 + A)$
10 × 6	0.071	$Q = V(14X^2 + A)$
10 × 5	0.065	$Q = V(15X^2 + A)$
10 × 4	0.059	$Q = V(17X^2 + A)$
10 × 3	0.049	$Q = V(20X^2 + A)$
10 × 2	0.037	$Q = V(27X^2 + A)$
10 × 1	0.020	$Q = V(50X^2 + A)$

Even though the true velocity contours of actual exhaust hoods are not strictly spherical or cylindrical, the error introduced by computing ventilating requirements on the basis of simple spheres, cylinders, or planes according to the hood design is usually far less than the error entailed in estimating a successful *capture* or *dust control* velocity. Such estimates of required capture velocities may easily be 200 or 300 per cent in error if the field conditions are not carefully analyzed. Laboratory studies of capture velocities thus far have not been able to incorporate the highly complex disturbances encountered in most field applications. The ventilation designer must fill in this gap with all the experience and judgment he can command.

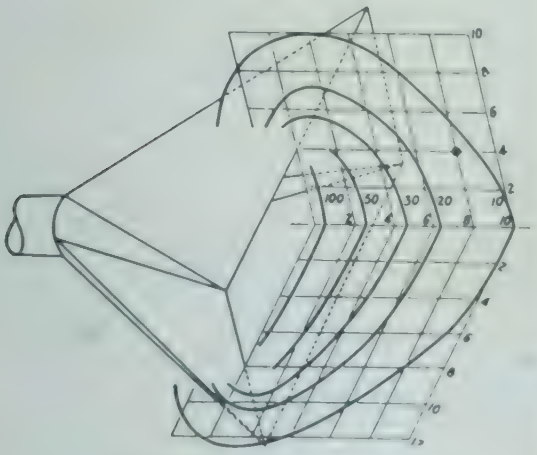

Figure 7. Actual velocity contours and streamlines for air flow into a rectangular hood. (Courtesy J. M. DallaValle.)

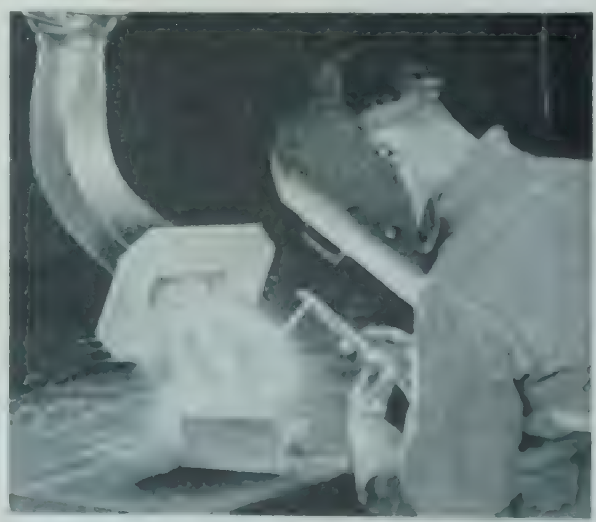

Figure 8. Flanged exhaust hood for arc welding. (Courtesy Ruemelin Manufacturing Co., Milwaukee.)

4. Air Velocities for Control of Air Contaminants

The escape of air contaminants can be prevented by the use of sufficient "capture velocity" at the point where the manufacturing process generates or releases the contaminant. The required velocity is estimated with consideration of drafts, traffic disturbances, convection currents, and mechanical motions around the ventilated process. Such estimates are very often necessarily speculative or trial-and-error values combining the designer's experience and judgment, and his appraisal of scattered reports of laboratory and field studies. Current research on this problem is certain to reveal, for future design, more rational ways to determine capture velocities for many types of processes.

Table 8 recommends tentative air velocities for the local-exhaust control of gases, vapors and fumes, and dusts below 10 μ in size. The density of gaseous contaminants is ignored on the assumption that the concentration in the air will be less than 1 per cent or 10,000 p.p.m. All figures are air velocities in linear feet per minute; they are not hood-face velocities unless the process under control is at or within the hood opening. These velocities are recommended for applications where no baffles or windbreakers can be installed for deflection of cross drafts.

TABLE 8

Recommended Velocities to Prevent the Escape of Air Contaminants

	Process at room temperature	Process several hundred degrees F. above room temperature, creating strong thermal updrafts		
Horizontal draft condition	All hood types	Updraft hood	Sidedraft hood	Downdraft hood[a]
Negligible (50 l.f.m.)	75	100	200	300
Slight (100 l.f.m.)	150	200	300	400
Moderate (200 l.f.m.)	300	300	400	500
Strong (300 l.f.m.)	400	400	400	500

[a] Generally an unsatisfactory choice for hot processes.

Table 8 does not incorporate the important factor of the speed or force of dust or mist generated by certain kinds of industrial process. Spray-painting guns discharge a mist that has sufficient velocity to rebound with considerable force from large flat surfaces perpendicular to the line of aim. Stone cutting, crushing, and milling give a high initial velocity to particulate matter. Grinding, polishing, and buffing wheels remove particles at high speed, and also induce high-velocity air currents at their peripheries. Pneumatic tools scatter large and fine particles in all directions, and the designer must decide how large a piece he will attempt to capture with his exhaust hood. Capture velocities for this class of machine and hand tools range from 500 to 5000 l.f.m. depending on the degree of control desired.[10]

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[10] W. C. L. Hemeon, *Plant and Process Ventilation*. Industrial Press, New York, 1955.

Successful application of very high-velocity, low-volume local exhaust has been reported by British investigators, which is of special interest to those confronted with the control of dust from portable devices.[11]

Tables 9 and 10 are recommendations from the American Standards Association on the fundamentals of exhaust systems.[12]

TABLE 9

Range of Capture Velocities

Condition of dispersion of contaminant	Examples	Capture velocity (l.f.m.)
Released with no velocity into quiet air	Evaporation from tanks; degreasing, plating, pickling	50–100
Released at low velocity into moderately still air	Spray booths; intermittent container filling; low speed conveyor transfers; welding	100–200
Active generation into zone of rapid air motion	Spray painting in shallow booths; barrel filling; conveyor loading; crushers	200–500
Released at high initial velocity into zone of very rapid air motion	Grinding; abrasive blasting, tumbling	500–2000

TABLE 10

Capture Velocities for Specific Operations
(Velocity at furthest point of source unless otherwise specified.)

Operation	Capture velocity (l.f.m.)	Remarks
Abrasive blasting		
Cabinets	500	Virtually complete enclosure
Rooms	60–100	Downdraft in room
Bagging		
Paper bags	100	Booth or enclosure
Cloth bags	200	Booth or enclosure
	400	At point of origin (local exh.)
Barrel filling	75–100	Point of origin
Bins and hopper	150–200	Face of enclosing hood
Bottle washing	150–250	Face of booth
Conveyor transfer points	150–200	Face of enclosing hood
Core sanding	100	Point of origin (sanding lathe)
Forge (hand operated)	200	Face of enclosure
Foundry screens		
Cylindrical	400	Openings in enclosure
Flat deck	200	Openings in enclosure

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[11] W. B. Lawrie, A. T. Holman, and E. B. James, *Proceedings of the Conference on Foundry Ventilation and Dust Control*, Harrogate, England, 1955. The British Cast Iron Research Association, Birmingham, 1956, pp. 245–54.

[12] American Standard Fundamentals Relating to the Design and Operation of Exhaust Systems, Z9, American Standards Association, New York, 1936 (revision in process, 1958).

TABLE 10 (*continued*)

Operation	Capture velocity (l.f.m.)	Remarks
Foundry shakeout	200	Openings in enclosure
	250	Cold castings, downdraft
	600	Hot castings, downdraft
Furnaces		
Aluminum	150–200	Openings in enclosure
Brass	200–250	Openings in enclosure
Grain elevators		
Boot and head	500	Face of enclosing hood
Granite cutting		
Hand tool	200	Point of origin—suspended hood
Surfacing machine	1500	Point of origin
All tools	1500	Face of enclosing hood
Grinding		
Disc and portable	200–400	Downdraft grilles in bench or floor
Swing Frame	100–150	Face of booth
Kitchen range	100–150	Face of canopy
Laboratory hood	100–150	Face of hood, door open
	125–200	Downdraft through bench grille
Metallizing (toxic materials require air-line respirators)		
Toxic (lead, cadmium)	200	Face of enclosing booth
Nontoxic (steel, aluminum)	125	Face of enclosing booth
	200	Face of local hood
Mixers		
Sand	100–200	Face of enclosure
Packaging machines	50–100	Face of booth
	75–150	Downdraft
	100–400	Openings in complete enclosure
Paint spray	100–200	At face of booth. Depends on size and depth of booth, size of work
Pharmaceutical coating pans	100–200	At point of escape (opening of pan)
Pottery		
Dippers mangle	500	Point of origin
Biscuit brushing	750	Point of origin
Aerographing	100–150	Face of booth
Quartz fusing	150–200	Face of booth. Varies with size work.
Rubber rolls (calenders)	75–100	Hood opening
Silver soldering	100	Point of origin
Steam kettles	150	Face of canopy
Tanks		
Degreasing	50	Point of origin
Dip (Benzol)	150	Openings in partial enclosure
Pickling	75–100	Point of origin
Plating	50–100	Point of origin
Quench	100	Face of hood opening
Steam	75–100	Point of origin
Welding (arc)	100–200	Point of origin (suspended hood)
	100	Face of enclosing booth

5. *Face Velocity*

Face velocity is not enough information for estimating air-flow requirements. It is necessary to visualize the probable boundaries of the zone in space through which contaminated air can move away from the updraft, sidedraft, or downdraft hood. The approximate surface area of this imaginary zone is then computed, by plane, cylindrical, or spherical geometry, and multiplied by the best estimate of controlling air velocity. The hood face velocity is simply the result of its face area determined by mechanical considerations, and the total air flow to provide the required velocity toward or across the *zone of escape*. It is important to realize that, as shown in Figure 6, exhaust hoods draw air from all directions, unless the region of flow is predetermined by solid baffle plates, flanges, walls, or channels. Therefore, when the *sphere of influence* of an exhaust hood of any type is being estimated, all directions must be accounted for (*a*) as points from which air flow is desired, (*b*) as places where the air flow is prevented by solid obstructions, or (*c*) as points from which it is fully understood that air will flow wastefully, against the designer's wish.

6. *Specific Gravity of Gases and Vapors*

It is frequently stated that gases or vapors heavier than air should be ventilated downward, and those lighter than air should be removed from the room by updraft methods. Experience and research[13] indicate that it is quite important to consider the distribution, concentration, and temperature of the gas or vapor in the air before drawing any conclusion about the relative merits of updraft and downdraft systems of ventilation. This is especially true of general ventilation, where the forces influencing the rate of gas or vapor diffusion are complex and uncertain.

The following example illustrates the significance of vapor concentration:

Assume: that air contains 1 per cent or 10,000 p.p.m. of a vapor with a specific gravity of 5.0; assume also that the vapor is well mixed with the air in the ventilated area as a result of drafts, plant activity, and convection currents.

Then: air constitutes 99 parts having a sp. gr. of 1.0, vapor constitutes 1 part having a sp. gr. of 5.0,

$$
\begin{array}{l}
0.99 \times 1.0 = 0.99 \\
0.01 \times 5.0 = 0.05 \\
\hline
\qquad\qquad\quad 1.04 = \text{"effective" sp. gr. of the air-vapor mixture.}
\end{array}
$$

Therefore, the above mixture, compared with incoming clean air, would have a tendency to move downward expressed by the ratio 104/100, and not by the ratio 5/1, as is frequently implied. This means that the effects of drafts, window ventilation, traffic disturbances, or process heat can easily dwarf the effect of specific gravity.

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[13] W. N. Witheridge and H. T. Walworth, *J. Ind. Hyg. Toxicol.*, **22**, 175 (May, 1940).

Cleaning or degreasing liquids used on tables or at fairly stationary locations can be exhausted from the area by sufficient downdraft grille ventilation, whether the vapors are heavier or lighter than air. Updraft or backdraft hood ventilation is also practical if the correct amount of air is removed according to the distance of the hood from the point of operation. The important objection to updraft ventilation is *not* that it does not lift vapors that are heavier than air (which it does very well, in fact, at proper air-flow rates), but that it may draw these vapors across the worker's breathing zone. However, when a sufficient volume of upward air movement is utilized, even the objection to drawing the contaminant across the breathing zone may be "splitting hairs" in cases where other forms of ventilation are exceptionally difficult to apply.

7. Canopy Hood Ventilation

Figure 9 is a diagram of the familiar canopy or overhead hood. Simplified equations are suggested for estimating the correct amounts of ventilation for such hoods. Although the diagonal dot-dash line in the diagram should be considered the true "outer face" of the hood for the purpose of ventilation estimates, the four

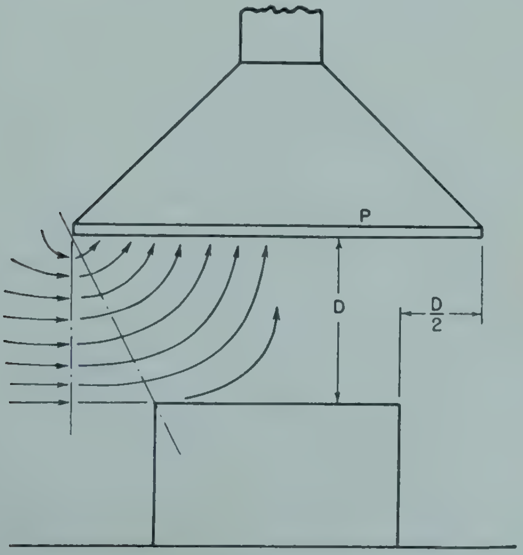

Figure 9. Updraft or canopy-hood ventilation: c.f.m. = 75 DP (when drafts are negligible); c.f.m. = 100 DP (designers' popular choice); c.f.m. = 150 DP (in presence of moderate drafts); c.f.m. = 300 DP (near strong, steady drafts); where c.f.m. is required air flow in cubic feet per minute; D is height of hood edge in feet above the point of air contamination; P is perimeter of hood at lower edge in feet, including only those sides open to the room; $^D/_2$ is extension of hood in feet beyond the source of air contamination on all sides open to the room. Constants in these equations are based on a hood extension of $^D/_2$. If the actual extension is less, compute the c.f.m. by assuming a $^D/_2$ extension and use this resulting quantity of air flow divided by the hood area to determine the "face velocity" of the hood, if such a specification is required.

simple equations given make sufficient allowance for the resulting *geometric* error of ignoring this angle and the *aerodynamic* error of ignoring the air velocity gradient between the hood edge and the ventilated process. In fact, the selection of the proper control velocity for use with these or similar equations may be much more difficult than the correct estimate of the face opening.

8. Sidedraft or Backdraft Hoods

The flow of air in this case is horizontal, preferably from the worker, across the source of contaminant and into the hood. Sidedraft hoods have the advantage of offering no overhead obstruction when parts must be moved about with cranes or hand hoists (Figure 10). It is also easier to keep the worker in a clean-air zone than when he works under a canopy hood. Ventilation requirements are greater with sidedraft hoods than with canopy hoods whenever there is a natural tendency of the air to rise above a cooler surrounding atmosphere. Sidedraft hoods operate practically the same as booths if the hood can be located close to the source of dust or vapor. If they must operate from a distance, they become nothing but an atmospheric "low spot" toward which air will flow from all directions, including the desired direction. As in the case of canopy hoods, we must visualize the probable "zone of escape" or route by which the air will try to escape with its contaminant. To counteract this tendency we must determine an effective "zone of influence" for the exhaust hood.

"Push-pull" systems are a novel variation of the sidedraft hood. On one side of the source of dust is placed a sidedraft exhaust hood. On the opposite side a device is placed to blow air across the dust source and into the exhaust hood. In practice, this method has the serious disadvantage that a blowing nozzle tends to remove the dust from an object that passes through the high-velocity air stream; consequently a greater exhaust volume must be used than if the system were "pull-pull" or exhaust on both sides of the process (Figure 11).

9. Downdraft Hoods

Hoods of this type draw the air downward across the process. They are most common in the form of perforated or grille-top tables and benches upon which the work is placed (Figure 2), but have been used in very large sizes covering a substantial portion of a workroom floor. They have the advantage of minimum interference with the work, but are costly to install and are troublesome to maintain if large quantities of dust are handled. They are more successful in the large floor sizes if installed above the ground floor so that servicing can be done readily from the floor below the ventilated process. For dust handling, the downdraft hood may also be part of a hopper and conveyor mechanism for carrying off heavy dust particles not removed by the ventilating ducts.

A major disadvantage of the downdraft method is the trouble encountered with hot processes that create a strong thermal updraft opposing the air currents

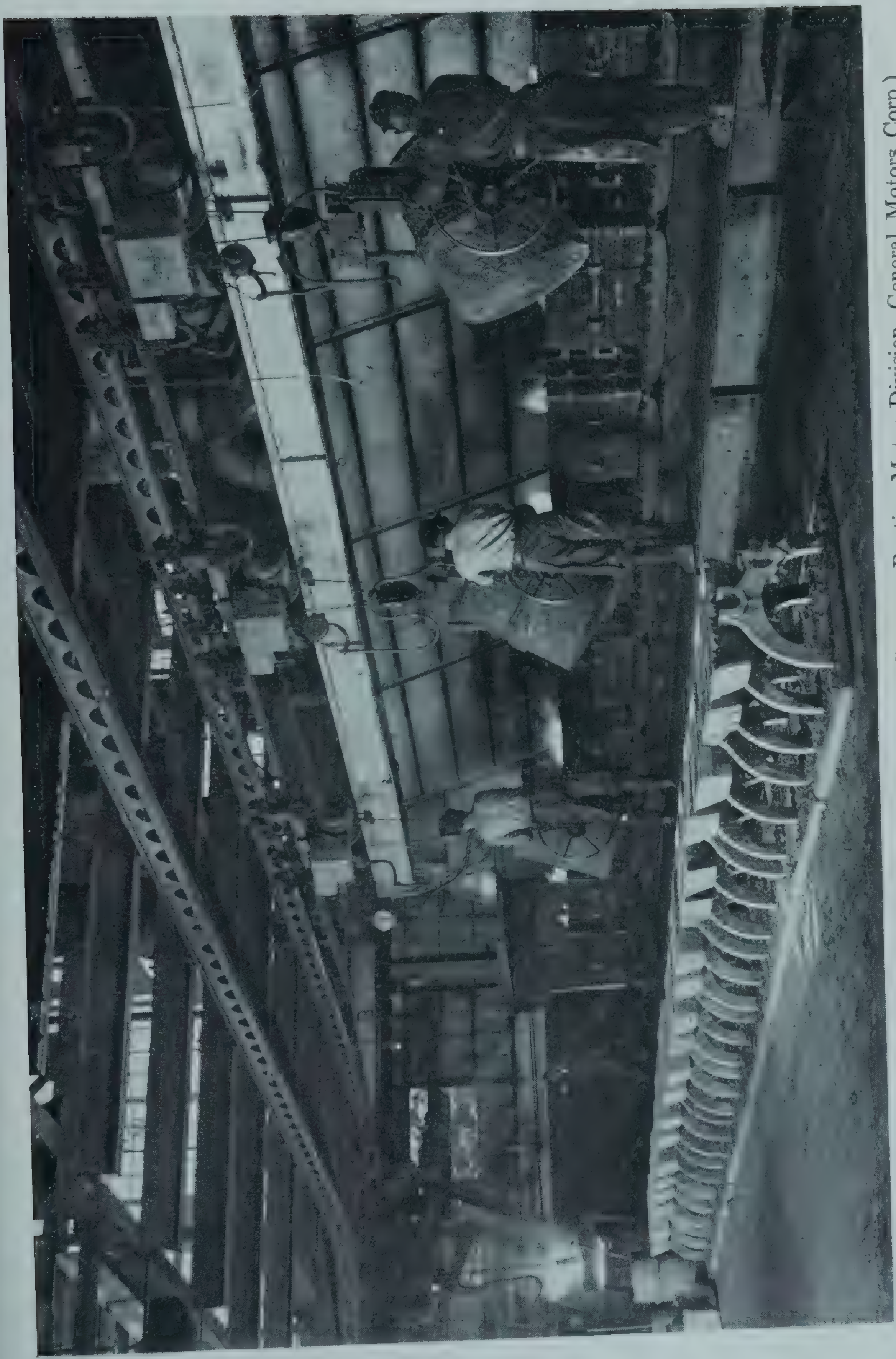

Figure 10. Sidedraft exhaust hood for casting shakeout. (Courtesy Pontiac Motor Division, General Motors Corp.)

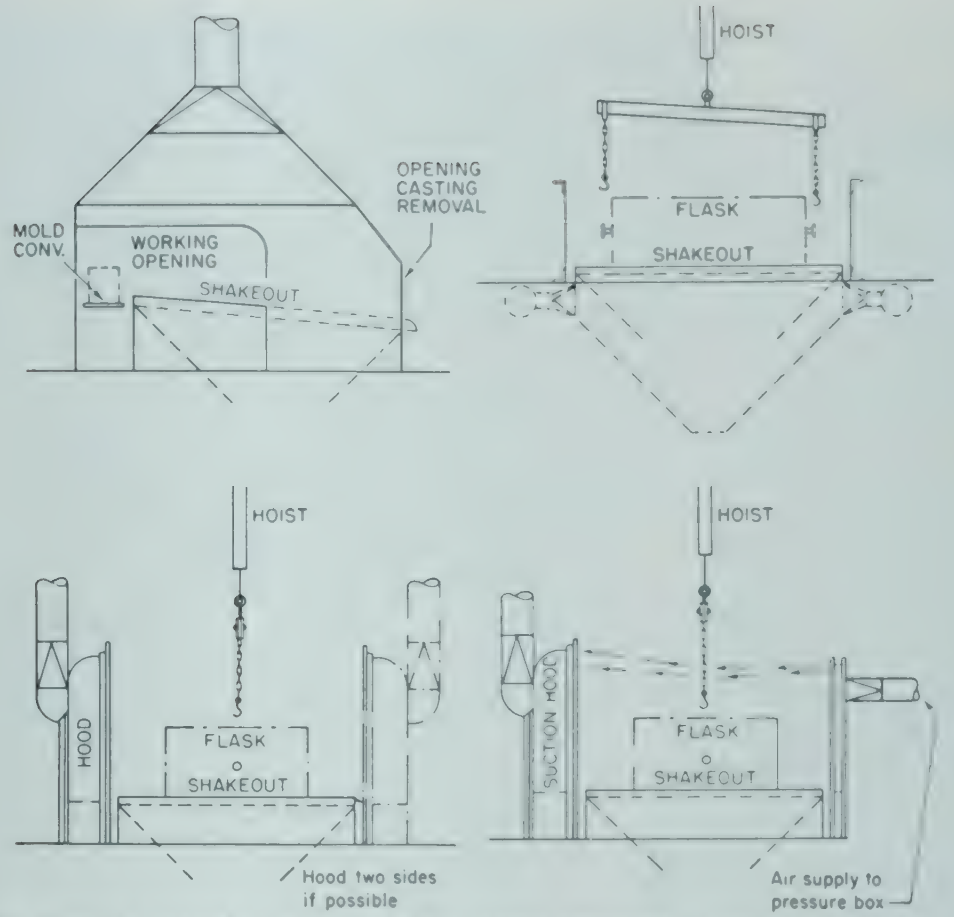

Figure 11. Several methods of ventilating shakeout processes. (From J. M. Kane, *Foundry*, **66**, 30 (January, 1938).)

moving down into the hood. To succeed under such conditions the air velocity downward must be generously in excess of the thermal updraft velocity. Another problem is the inevitable obstruction created by the work as it is placed upon the grille or openwork of the downdraft hood. The solution is to provide a grille considerably larger than the product to permit the required amount of air to pass down alongside the work fast enough to oppose crossdrafts and thermal effects.

10. Slot Exhaust Ventilation for Tank Processes

Figure 12 illustrates the slot or lateral-exhaust type of ventilation commonly applied to tanks for cleaning or degreasing, stripping, paint dipping, heat treating, anodizing, electroplating, and deplating. The air velocity into the exhaust slot is determined by the total quantity of air flow required to suppress or hold the contaminant within the tank, and the size of slot selected by mechanical considerations.

The *minimum* practical slot velocity for the design of Figure 12 is about 1000 l.f.m. in the interest of reasonably uniform distribution of air flow, when a single duct connection is used with slot extending around the tank. Lower velocities will

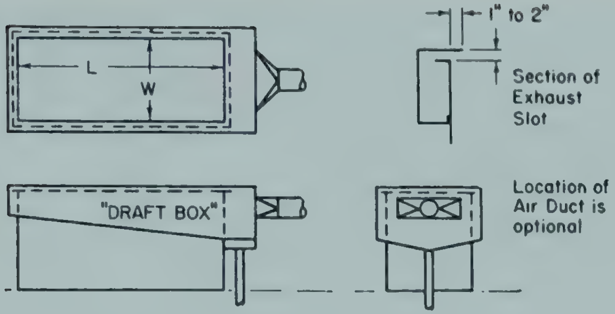

Figure 12. Slot exhaust ventilation for tank processes. Slope draft box to drain for flushing purposes; provide drain pipe with water seal or trap deep enough to prevent air flow up through pipe. An alternate method of draft box design is extension to the floor to connect with ducts below floor level.

give uniform distribution only when several duct connections can be made to the "draft box" or when the box or manifold is unusually large.

The *maximum* practical slot velocity is about 3000 l.f.m. in the interest of power economy, and minimum entrainment of mists or agitation of tank contents. Higher air velocities through very narrow slots *may* improve the uniformity of air distribution around the tank when the mechanical design or construction of ductwork is not good, but they should not be used unless power cost is of no consequence, or unlimited exhaust fan capacity is available.

The quantity of air flow required is determined by the equation:

$$\text{c.f.m.} = (\text{volume factor})\ (L)\ (W)$$

where c.f.m. = the total air flow in c.f.m., L = length of tank in feet, and W = width of tank in feet. *Volume factors* are suggested in Table 11.

TABLE 11

Air Volume Factors for Tank Ventilation[a]

Volume factor (c.f.m./sq. ft.)	Process or application
50	Solvent or vapor degreaser (trichloroethylene)
100	Hot water rinsing tank (nuisance control)
150	Chromium electroplating, cyanide solution
150	Plating solutions giving off much gas or mist
150	Muriatic acid (HCl) pickling
150	Molten salt baths for heat-treating
150	Aluminum anodizing
200	Electrolytic cleaning with sodium hydroxide
200	Hot caustic or alkali cleaning or degreasing
200	Boiling water solutions (steam and mist control)
250	Stripping with concentrated nitric acid
250	Stripping with concentrated nitric and sulfuric acids
250	Hot nitric-hydrofluoric acid pickling
250	Hot sulfuric acid pickling

[a] See also recommendations in American Standard for Ventilation and Safe Operation of Open-Surface Tanks, Z9.1-1951. American Standards Association, New York, 1951.

An important consideration in selecting the proper volume factor for electroplating is electrode efficiency. The electrolytic efficiency at the cathode and anode determine the amount of gas evolved, which in turn determines the amount of mist generated at the liquid surface. Failure to investigate this fact more carefully as it applies to operations in widely different plants, products, and platings is responsible for some of the discrepancies observed between ventilation rates initially specified and those actually required in full production.

11. Tailpipe Exhaust Systems for Internal-Combustion Engines

There are two methods of applying local exhaust to the tailpipes of automobiles and trucks for control of carbon monoxide and smoke in repair garages. The *overhead system* is favored for its ease of maintenance and simplicity of installation. It is avoided by some proprietors who desire to create the best possible appearance in their garage in keeping with the trend toward simplified and streamlined interior construction.

The *undergound system* (Figures 13 and 14) fulfills the desire to conceal the ventilating equipment, and is highly effective when carefully designed for easy maintenance. Since dirt, water, oil, and gasoline all may collect in the underground main, provisions must be made for drainage and periodic cleaning. Because of the danger of accumulation of flammable liquids, design should be based on continuous operation of the exhaust fan with some air flowing through each section of the system at all times. The drain to the sewer or sump must be provided with a trap

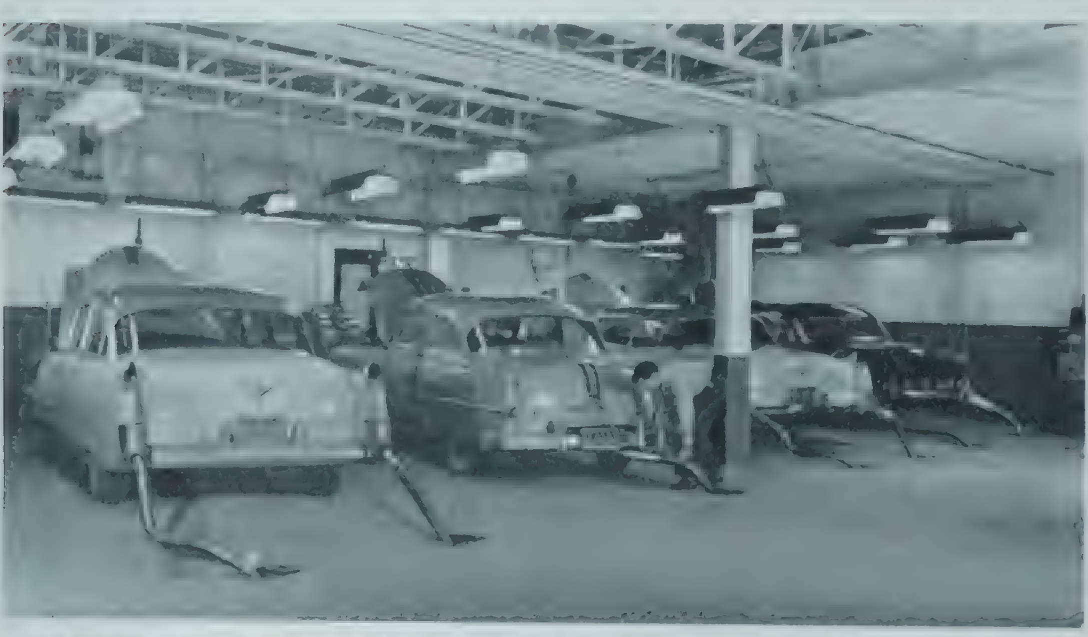

Figure 13. Floor-type tailpipe exhaust system for service garages. (Courtesy Kent-Moore Organization, Inc., Detroit.)

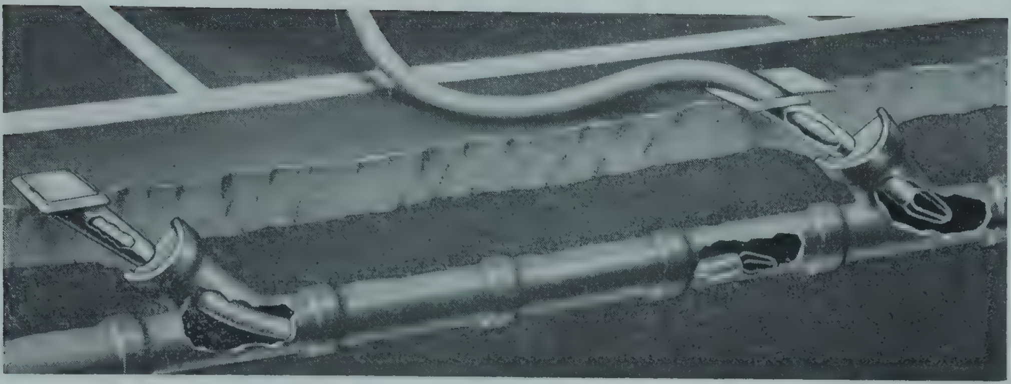

Figure 14. Detail of underground installation of tailpipe exhaust system. (Courtesy Kent-Moore Organization, Inc., Detroit.)

sufficiently high to prevent surge of water back into the exhaust-fan line as a result of the negative pressure created.

The air flow required at the end of the flexible conduits varies with the size of engine serviced, and is generally selected to be greater than the volume of exhaust gases discharged when the engine is operated at fairly high speed. The end of the flexible duct is slightly larger than the vehicle tailpipe to permit some room air to enter the system at this point. This prevents leakage and compensates for the variability in engine speed or displacement.

The following air-flow rates per flexible duct have given satisfactory control in many garages: automobiles and light trucks, 100 c.f.m.; heavy gasoline engine trucks, 200 c.f.m.; diesel engine trucks, 300 c.f.m. The high rate for diesel engines is due in part to the highly irritating nature of the combustion products. Air velocities in the main ducts can be in the range of 1000–2000 l.f.m. Flexible branch

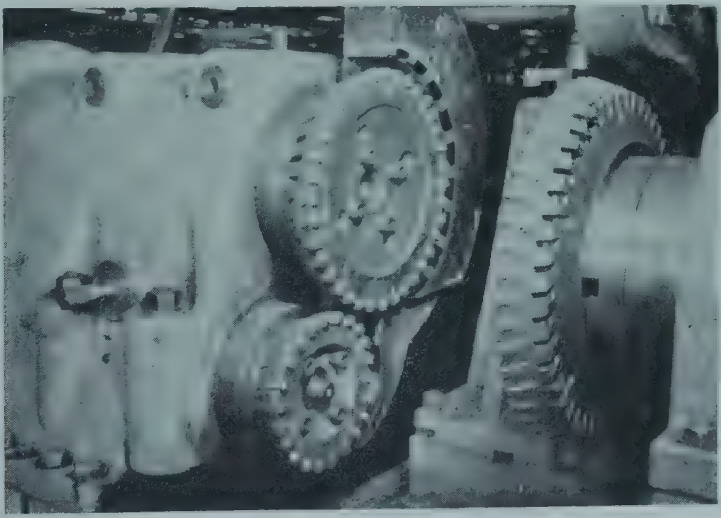

Figure 15. Example of hoods for cast-iron milling operations. (Courtesy Detroit Diesel Engine Division, General Motors Corp.)

ducts should be 2½ to 4 inches in diameter to avoid excessive velocity and air-flow resistance.

12. Special or Irregular-Shaped Hoods

The most familiar example of this group is the kind of hood installed on grinding, polishing, buffing, or sanding wheels and belts. The shape is determined largely by the outlines or contours of the rotary device to be ventilated. These hoods

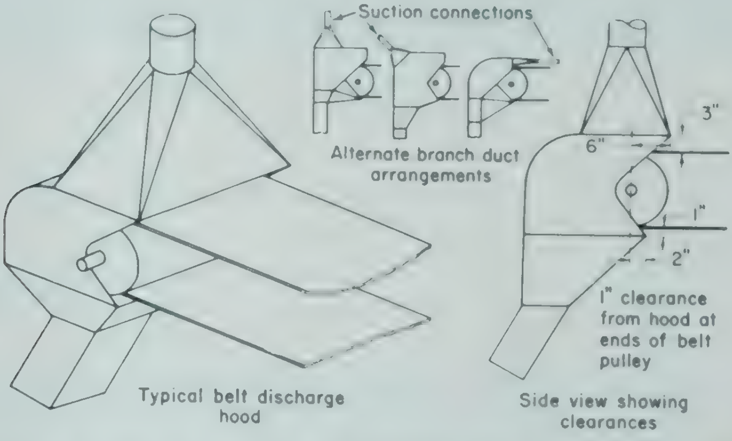
Suction connections
Alternate branch duct arrangements
3"
6"
1"
2"
1" clearance from hood at ends of belt pulley
Typical belt discharge hood
Side view showing clearances

Figure 16. Variation in design of hoods for conveyor-belt transfer stations. (Courtesy Mill Mutual Fire Prevention Bureau, Chicago.)

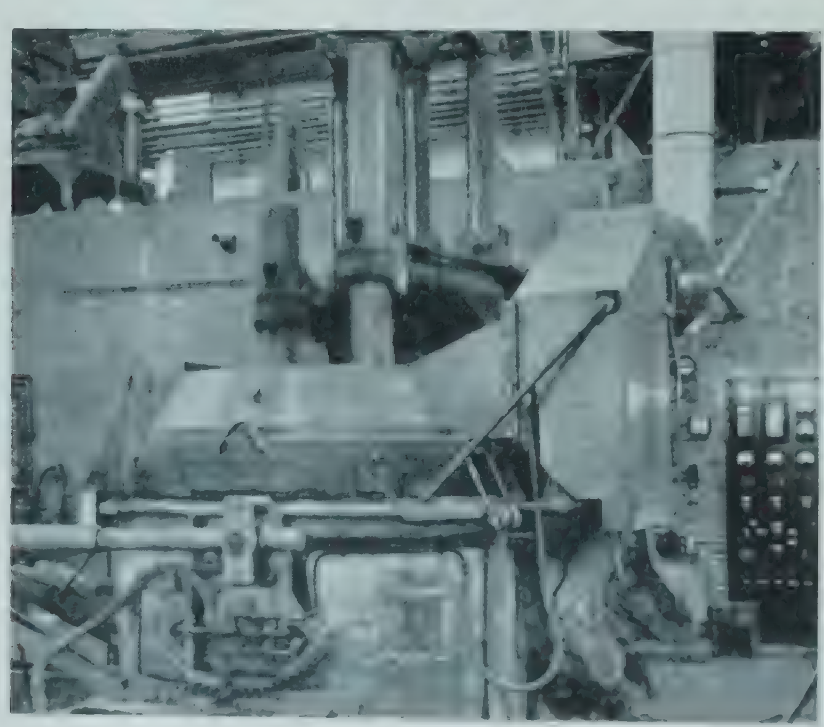

Figure 17. Local exhaust hood for electric furnaces. (Courtesy American Air Filter Co Louisville.)

should be custom-designed to enclose the dust, fume, vapor, or gas source as much as possible, and yet remain out of the operator's way so that he can work efficiently.

Other examples are hoods for woodworking machines, textile machines, conveyors and bagging stations, pneumatic rock drills and stone-surfacing machines. A few special types are illustrated in Figures 15, 16, and 17.

Table 12 suggests ventilation rates for grinding, polishing, and buffing wheels. This schedule is based on the concept that the ventilation rate must depend on the quality of hood provided. Thus, if polishing or buffing wheels cannot be as completely enclosed as grinding wheels, larger volumes of air will be necessary to capture the generated dust and lint.

TABLE 12

Minimum Exhaust Ventilation for Grinding, Buffing, and Polishing Wheels

Maximum wheel diam.[a] (inches)	Minimum air volumes (c.f.m.)	
	Good wheel enclosure[b]	Poor wheel enclosure[c]
1–4	200	300
5–9	300	450
10–14	400	600
15–19	550	800
20–24	700	1000
25–29	900	1400
30–36	1200	1800

[a] Largest wheel that can be used within the exhaust hood.

[b] Not more than 25 per cent of wheel periphery and wheel sides exposed.

[c] Buffing and polishing wheels generally require the larger air quantities because of "poor wheel enclosure."

Kane[14] compiled a useful list of the air flows representing good practice for the control of certain dusty processes, and Table 13 is adapted from his original tabulation. See also the manual *Industrial Ventilation* by the American Conference of Governmental Industrial Hygienists for additional recommendations.

C. CENTRAL VS. UNIT EXHAUST SYSTEMS

In many industrial plants the operating personnel are driven to seek the most flexible equipment for the constant shuffling and reshuffling of plant layout and operational sequence. Process ventilation is no exception. Some plants are in a stage of transition from elaborate interconnected centralized duct systems to the individual unit exhaust and air-cleaning devices for single or small groups of industrial machines. The higher price paid for a large collection of individual exhaust ventilating units is the price of flexibility.

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[14] J. M. Kane, *Heating and Ventilating*, **42**, 68 (November, 1945).

TABLE 13

Volumes of Air Exhaust for Dust-Producing Equipment

Dust-producing equipment	Exhaust hood type	Air-flow requirements
Abrasive-blast rooms (sand, grit, or shot)	Tight enclosure with air inlets (usually in roof)	60–100 l.f.m. downdraft (long rooms of tunnel proportions 100 l.f.m. crossdraft). Exhaust volume should be sufficient to provide visibility for operator. Sand as abrasive, or castings with cores, or heavy molding sand deposits require highest range.
Abrasive-blast cabinets	Tight enclosure with access openings	20 air changes per minute but not less than 500 l.f.m. through all openings.
Bagging machines	Booth or enclosure. Provide spillage hopper	Paper bags, 100 c.f.m. per square foot open area. Cloth bags, 200 c.f.m. per square foot open area.
Belt conveyors	Hoods at transfer point	Belt speeds less than 200 l.f.m.—350 c.f.m. per foot of belt width, but not less than 150 l.f.m. through open area. Belt speeds over 200 l.f.m.—500 c.f.m. per foot of belt width but not less than 200 l.f.m. through open area.
Belt wipers (may be required with high-speed belts)	Tight-fitting hood held against underside of belt	200 c.f.m. per foot of belt width. Requires high hood suction and high conveying velocities. Mechanical brushing or wiping often used in conjunction with hood.
Bins (closed bin top)	Connect to bin top away from feed point	150–200 l.f.m. through open area at feed points, but not less than 0.5 c.f.m. per cubic foot of bin capacity.
Bucket elevators	Tight casing required	100 c.f.m. per square foot of elevator casing cross section. (Exhaust from elevator head.) To maintain indraft in casing only. Additional exhaust at elevator boot and discharge unless tight connections are employed.
Ceramics		
Dry pan	Enclosure	200 l.f.m. through openings.
Dry press	Local at die	500 c.f.m.
Fettling, brushing, sagger filling, and unloading	Downdraft or side hood	100–150 c.f.m. per square foot of plan area of dust-producing operation.

This transition is similar to the gradual shift from overhead lineshaft drives in nineteenth century plants to the individual motor drives for the machinery of contemporary mass production. There are still some factories that have not converted their machine shops from flat-belt drives off overhead lineshafts to individual electric motor power for each machine. In such shops the rearrangement of machinery is a minor problem, and the need for self-contained

TABLE 13 (*continued*)

Dust-producing equipment	Exhaust hood type	Air-flow requirements
Grinders, portable and flexible shaft	Downdraft grilles. Use side shields where possible	Bench type, 200–400 c.f.m. per square foot of exhaust grille but not less than 150 c.f.m. per square foot of plan working area. Floor grille, 200–400 c.f.m. per square foot of exhaust grille but not less than 100 c.f.m. per square foot of plan working area.
Mixers	Enclosure	100–200 l.f.m. through working and inspection openings. Where mixer causes pronounced agitation, use indraft velocities in the higher range.
Pharmaceuticals, coating pans	Narrow side hood	100–150 l.f.m. through openings. If heated air is supplied to coating pan, this must be added to air entering openings to obtain total exhaust volume.
Shakeouts Foundry	Enclosure	200 l.f.m. through all openings in enclosure; but not less than 200 c.f.m. per square foot of grate area.
	Side hood. Use side shields where possible	400–600 c.f.m. per square foot of shakeout grate area.
Screens Vibrating, flat deck	Enclosure	150–200 l.f.m. indraft through hood openings, but not less than 25–50 c.f.m. per square foot of screen area.
Cylindrical	Enclosure	100 c.f.m. per square foot of circular cross section but not less than 400 l.f.m. indraft through openings in enclosure.
Tumbling mills, hollow trunnion type	Exhaust connection by manufacturer	Use branch diameter same size as exhaust outlet. For round mills branch diameter should be one sixth diameter of mill; for square mills, branch diameter should be 1 in. plus one sixth side dimension of mill.
Miscellaneous packaging machines, granulators, enclosed dust-producing units	Complete enclosure	100–400 l.f.m. indraft through inspection or working openings, but not less than 25 c.f.m. per square foot of enclosed plan area. Volume will normally be insufficient to prevent dust settling on floor and equipment within enclosure.

units may not be great enough to justify the cost of converting the method of power transmission. Likewise, there are many exhaust ventilating jobs that do not need to contend with the continuous relocation of processes; and the use of a centralized duct system with a single fan, motor, and air cleaner remains the best and most economical arrangement, both from the standpoint of installation costs and maintenance expenses.

IV. Aeromotive Methods and Equipment

The forces available for ventilation are here considered as either natural or mechanical, as in the discussion of general ventilation.

A. NATURAL AEROMOTIVE FORCES

Natural ventilation may be *(1)* gravity, motivated by the thermal forces of convection, or *(2)* anemotive, created by wind pressure. These two natural forces operate together in most cases, and a study of their effects has led to the concept of the "neutral zone" in thermal ventilation, modified by experimentally verified wind-pressure corrections.

Emswiler and Randall[15] gave the following analysis of the combined action of wind and thermal forces in producing air flow through a building:

> Even without any wind, a difference of temperature inside and outside will cause the pressure state inside to be less than that outside at the ground, and greater near the roof, and inflow will occur at lower windows and outflow at upper windows. If the building is tall and open throughout from bottom to top, or if arranged in stories in free communication from one to another, and if the temperature difference is great, the pressure difference created at a point near the ground and also at a point near the roof may be considerable. Thus, in a building 200 ft. high with 70° F. difference in temperature, this force alone causing inflow at the ground and outflow at the top, may easily exceed 0.20 in. of water, which is the equivalent of a twenty-mile wind. If the building is multiple storied and there is absolutely no communication between stories, then the force of temperature difference is effectually nullified, or rather reduced to an amount proportional to the height of a single story. However, there is always some communication by means of stairs and otherwise, so that the force of temperature difference is always operative in some degree.
>
> If the wind blows against a window of a building that is tightly sealed at all other points of possible ingress or egress of air, there will be no continuous infiltration at the window, because the temporary excess of pressure outside will soon be equalized by a momentary inflow. If the building has an outlet of exactly the same area as the presumed infiltration area of the window, and this outlet opens into a region of neutral pressure, then the pressure in the room will be half as much as that produced by the wind outside. Infiltration will take place through the window, but with only half the force of the wind pressure. Something like this is what occurs in any building. Whatever air gets in at inflow points must escape somewhere else. In order to force the air out, there must be a greater pressure inside somewhere than that which prevails immediately outside. The inside pressure automatically assumes a value that will give the necessary head for outflow through openings available, *so that the outflow quantity always balances the inflow* [italics ours].

1. *Wind Direction, Velocity, and Pressure*

Few locations in the United States have what is actually a "prevailing" wind direction, if this is taken to mean a direction from which the wind blows most of the time. Not over 5 per cent of the land receives wind from one general direction as much as 50 per cent of the time. Wind data collected by the Weather Bureau at stations located on the tops of high buildings cannot be taken as representative of ground conditions throughout the entire area. The observing stations in large cities are so located in order to sample a stratum of air that is unaffected by turbulence generated by surrounding structures.

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[15] J. E. Emswiler and W. C. Randall, *Trans. ASHVE*, **34**, 527 (1928).

The velocities of the winds at these elevated locations are higher than ground values would be if no obstructions existed. For those design problems where the minimum daylong wind velocity determines the quantity of natural ventilation to be expected, values about one half the indicated seasonal average velocities should be chosen. Average wind velocities throughout the United States range from 5 to 15 m.p.h. for all seasons of the year.[16]

In cases where an occasional gust of wind, or the pressure of high wind velocities for a few hours of a day would create dangerous reduction of ventilation on a system handling irritating or hazardous gases, vapors, or dusts, the ventilator must be protected against such pressures. It is evident that a substantial wind pressure applied to the side of a building in which a fan is mounted may seriously reduce the volume of air moved and may even reverse the direction of flow when the fan is not creating a high static pressure. Some type of baffle, "windbreaker," or automatic damper should be provided, or the fan should be selected for a higher static pressure to compensate for reasonable wind pressures above the average. Table 14 assembles some of the data needed for consideration of the wind velocity-pressure factor.

TABLE 14

Wind Velocity Pressure

Miles per hour	Linear feet per minute	Velocity pressure, VP[a] (inches of water)	Visible or physical effects
1	88	0.0005	Smoke rises vertically
2	176	0.0019	Direction of wind shown by smoke drift
3	264	0.0044	Moderate walking speed
4	352	0.0077	Fast walking speed
5	440	0.012	Wind felt on face; leaves rustle
10	880	0.048	Wind extends light flag
15	1320	0.11	Raises dust and loose paper
20	1760	0.19	Crested wavelets form on inland water
25	2200	0.30	Umbrellas used with difficulty
30	2640	0.44	Whole trees in motion
35	3080	0.59	Difficulty walking against wind
40	3520	0.77	Breaks twigs off trees
50	4400	1.2	Slight structural damage to buildings
60	5280	1.7	Considerable structural damage

[a] $VP = (\text{l.f.m.}/4000)^2 = 0.00048\,(\text{m.p.h.})^2$.

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[16] J. C. Albright, *Summer Weather Data*. The Marley Co., Kansas City, Kan., 1939.

2. Roof Ventilators

The application of motor-driven axial and centrifugal fans to stacks or vertical ducts for general ventilation is effective testimony that wind and heat-driven devices are not sufficiently dependable for the great majority of industrial applications. Wind velocities must be high and temperature differences large to permit the consistent and reliable operation of ventilators utilizing natural forces.

An effective combination for reliable ventilation is the use of a pivoted or oscillating roof ventilator with an axial-flow fan mounted in the base, as shown in Figure 18. This assures a positive, predictable flow of air; provides the fan with a discharge outlet that locates itself downstream with respect to the wind; and gives the fan substantial assistance instead of opposition at high wind velocities from any direction.

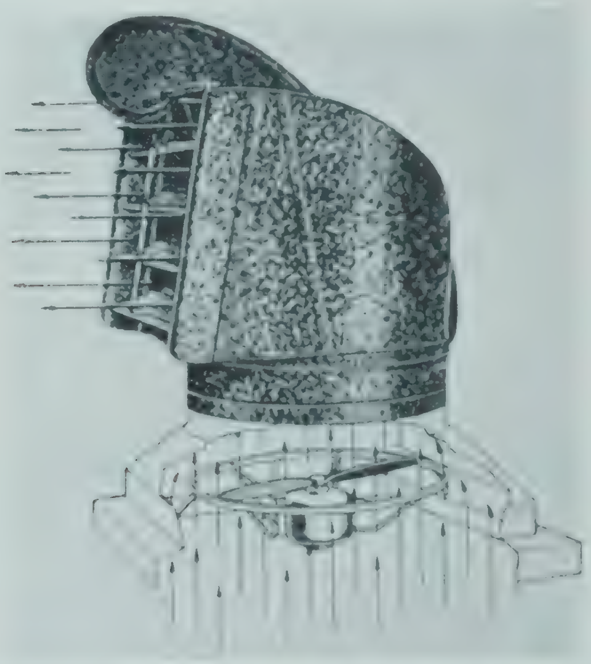

Figure 18. Pivoted roof ventilator combined with axial-flow fan. (Courtesy The Swartwout Co., Cleveland.)

For those who need to estimate the velocity of air flow through stationary "gravity" ventilators, an *approximate* empirical formula is available in terms of temperature difference in degrees F., height in feet between inlet and outlet, and moderate wind velocity in m.p.h. To apply this formula, the air-inlet area must not be less at any point than the stack or ventilator throat area.

$$\text{l.f.m.} = 10\sqrt{(\text{height in feet})\,(\text{temp. diff. in }^\circ\text{F.}) + 16\,(\text{m.p.h.})^2}$$

This equation ignores the variability in friction, turbulence, and entrance and discharge losses by assuming that the ventilator is about 50 per cent efficient in its utilization of the combined forces of wind and heat. It is not suitable for the accurate study of comparative performance of commercial ventilators, but is introduced here to demonstrate that velocities through stationary roof ventilators seldom exceed 500 l.f.m. Only at the high temperatures available with hot processes can high updraft velocities be anticipated.

Examples in the use of the above formula are: (*1*) at a height of 30 ft., temperature difference of 30° F., and zero wind velocity, the stack velocity is 300 l.f.m.; (*2*) at 10 m.p.h. wind and no temperature difference, the stack velocity is 400 l.f.m.; (*3*) at 30 ft. height, 30° F. differential, and 10 m.p.h. wind, the stack velocity is 500 l.f.m.; and (*4*) at 50 ft. height, 50° F. differential, and zero wind velocity, the stack velocity is 500 l.f.m.

3. High-Temperature Stacks

The theoretical static pressure or "draft" developed between two columns of air at a substantial temperature difference can be computed from the following simplified and approximate formula:

$$\text{SP in inches of water} = \frac{(\text{height in feet})\ (\text{temp. diff. in }^\circ\text{F.})}{32{,}000 + 70\ (\text{stack gas temp. in }^\circ\text{F.})}$$

Ordinarily only about 60 to 80 per cent of this theoretical draft is available, depending upon the stack diameter, nature of flue-gas entrance, and the velocity of air or gas flow.

For *available draft* in chimneys, where the flue-gas temperature is about 500° F. above the outdoor temperature, an approximate figure of 0.005 inch per foot of stack height is sometimes used.[17] An American Foundrymen's Code[18] made the following provisions with respect to "Chimney Exhausts":

> Any process or operation which is dependent on the combustion of fuels in its operation, and which can be so enclosed at all times so that there is no leakage of harmful gases or matter into the room atmosphere, may be exhausted to the outside by means of a natural draft chimney—provided the chimney temperature is *at least 300° F.*, and the chimney can be attached directly to the equipment.

Chemists and laboratory technicians have been aware, for many years, of the method of creating ventilation for their hoods by placing a gas burner at the base of the ventilating flue. They are also aware of the marked improvement in laboratory ventilation when this gravity or thermal type aeromotive force is replaced by a reliable motor-driven fan.

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[17] R. D. Madison, *Fan Engineering*. 5th ed., Buffalo Forge Co., Buffalo, N. Y., 1948.

[18] *Tentative Recommended Good Practice Code and Handbook on the Fundamentals of Design, Construction, Operation and Maintenance of Exhaust Systems.* American Foundrymen's Association, Chicago, 1938.

B. MECHANICAL AEROMOTIVE FORCES

1. *Fans: Blowers and Exhausters*

Rotating devices for the movement of air in either general or local ventilating systems are of two fundamental types. They are conveniently classified as either (*a*) *axial flow*, which includes long-blade propeller and disk fans, and very short-blade high-pressure axial fans; or (*b*) *radial flow*, or centrifugal fans, with the revolving element made of radial blades fastened to a central hub, or circumferential blades shaped to curve forward or backward with respect to the direction of rotation, and supported with a rim or disk fastened to the central hub (see manufacturers' catalogs for illustrations).

It is very important for those who inspect and test mechanical ventilating systems to know that axial and centrifugal fans may be further designated according to the effect that direction of rotation has on the direction of air flow. Reversing the rotation of any axial-flow fan or disk will reverse the direction of air flow through it, inasmuch as flow parallel to the axis of rotation, as an "air screw," is essential for membership in this class. However, the flow of air through a centrifugal device can be only radial, or from the center outward. This means that its direction of rotation does not determine the direction of air flow, but simply affects the quality of its performance. Consequently, the direction of air flow through a centrifugal exhauster or blower *cannot* be used as a remote or distant indication of its direction of rotation. Reverse flow through this type of fan means either (*a*) that is is not operating, or (*b*) that it is subjected to external pressures greater than it can develop at its operating speed. The second statement, of course, applies likewise to axial-flow fans.

a. Axial-flow or spiral-flow fan characteristics (air flow *does* reverse when rotation is reversed).

(*1*) Type: *long blade* propeller or disk on small hub; with or without circumferential support.
Duty: large volume, low pressure; best as "free flow" or low, stable resistance.
Power: *maximum* horsepower at zero air delivery with maximum resistance; power gradually falling as resistance decreases and air volume increases (this relationship might reverse at a small unstable section of the power-volume curve).
Efficiency: 30–40 per cent at optimum performance.

(*2*) Type: *short blade*, airfoil design with large streamlined hub, no circumferential support, designed especially for use within cylindrical ducts; control of power-pressure curve stability obtained by varying blade angles ("low," "medium," or "high" angle blades).
Duty: large volume, medium or high pressure; freedom of choice for position of mounting; potentially quieter than propeller or disk when operated near maximum air delivery, useful where installation space is at a premium, as on ships.
Power: *maximum* horsepower at zero delivery, but characterized by less difference between zero and maximum flow horsepower than for other fan types.
Efficiency: 50–70 per cent at optimum performance; higher efficiency due to airfoil design, guide vanes or "straighteners," and precision blade-tip clearances.

b. Centrifugal or radial-flow fan characteristics (air flow *does not* reverse when rotation is reversed).

(*1*) Type: *forward curve blade* in "squirrel cage" or circumferential support; blades usually wide and shallow.
Duty: large volume, low to medium pressure; quiet for low-speed operation.
Power: *minimum* horsepower at zero air delivery; power continuously rising with decreased resistance; *maximum* horsepower at "free delivery" with minimum resistance; this type has greatest danger of burning out motor if system resistance is suddenly decreased or is substantially less than anticipated in design.
Efficiency: 50–70 per cent at optimum performance.

(*2*) Type: *backward curve blade* in "squirrel cage" or circumferential support; blades wide and shallow; also may be backwardly inclined *straight* "steel plate" blade for heavy duty or pneumatic conveying.
Duty: large volume, medium to high pressure, with "nonoverloading" feature.
Power: *minimum* horsepower at zero air delivery; *maximum* horsepower near maximum air delivery, and near point of maximum efficiency.
Efficiency: 60–75 per cent at optimum performance.

(*3*) Type: *"S" curve blade,* outer section curved backward, inner section curved forward with respect to direction of rotation; with circumferential support or "squirrel cage."
Duty: large volume, medium to high pressure; nonoverloading; relatively low noise level for high-speed operation.
Power: *minimum* horsepower at zero delivery; *maximum* horsepower near maximum delivery and maximum efficiency.
Efficiency: 65–75 per cent at optimum performance.

(*4*) Type: *straight radial blade* or "paddle wheel" with either a "spider," disk, cone or circumferential ring support; blades often narrow and deep in a narrow, large diameter scroll.
Duty: small to medium volume, with medium to high pressure; suitable for conveying shavings, fibers or sticky materials; high suction for vacuum cleaning; inherently noisy at high-speed, high-pressure duty.
Power: *minimum* horsepower at zero delivery; *maximum* horsepower at maximum or "free" delivery.
Efficiency: 50–60 per cent at optimum performance.

c. Special wheels or rotors for centrifugal fans. Many varieties of wheels are produced for centrifugal fans to accommodate the wide range of supply and exhaust ventilating and pneumatic conveying applications. They can be made of almost any rigid material, to: (*1*) resist abrasion, (*2*) minimize corrosion, (*3*) prevent sparking, (*4*) avoid plugging, (*5*) minimize noise, (*6*) limit horsepower, (*7*) resist fire, (*8*) handle high-temperature air (*9*) reduce vibration, and (*10*) facilitate cleaning. This makes it evident that there is danger of false economy in the purchase of cheap fans and blowers for exhausting and conveying inasmuch as the motive power is the heart of the air-handling system.

d. Fan selection. The following check list indicates the amount of care required in the proper selection of centrifugal- or axial-flow fans. Items 1 and 2 are essential in every case, while in most cases many of the additional items must be given some thought: (*1*) c.f.m. of air to be moved; (*2*) static pressure against which this air must be moved; (*3*) permissible noise level or noise character of the environment; (*4*) whether constant or variable speed of operation is expected;

(5) type of motive power (AC, DC, compressed air, or heat engine); *(6)* direct or belt driven, and whether drive must be protected against air contaminants, heat, or excessive moisture; *(7)* kind of contaminants in air to pass through fan; *(8)* quantity of contaminants in air to pass through fan; *(9)* contaminants in the atmosphere *surrounding* the fan and motor, including potential explosion or fire hazard; *(10)* temperature of air or gas to pass *through* fan; *(11)* temperature of atmosphere *surrounding* fan and motor; *(12)* possibility of condensation within fan housing or scroll; *(13)* whether to be located before or after air-cleaning equipment; *(14)* size and shape of available space; *(15)* correct discharge direction for centrifugal fan to avoid unnecessary bends in ductwork.

e. Fan laws. These relationships or physical laws apply when a given fan and ventilating system are operated together under variable conditions of fan speed and air density:

Variable fan speed—constant air density

(1) Air volume (c.f.m.) varies directly with fan speed (r.p.m.).

(2) Static, velocity, and total pressures (S.P., V.P., T.P.) vary directly with the square of fan speed $(\text{r.p.m.})^2$.

(3) Horsepower (H.P.) varies directly with the cube of the fan speed $(\text{r.p.m.})^3$.

Constant fan speed—variable air density

(4) Air volume (c.f.m.) remains constant as air density varies.

(5) Static, velocity, and total pressures (S.P., V.P., T.P.) vary directly with air density (d).

(6) Horsepower (H.P.) varies directly with air density (d).

Constant weight of air delivered

(7) Fan speed (r.p.m.) varies inversely with air density (1/d).

(8) Static, velocity, and total pressures (S.P., V.P., T.P.) vary inversely with air density (1/d).

(9) Horsepower (H.P.) varies inversely with the square of air density $(1/d^2)$.

f. Standard air. Unless conditions require otherwise, the ventilating engineer usually assumes a standard air density of 0.075 pound per cubic foot, which is the approximate weight of air at sea level barometric pressure of 29.92 inches Hg and 70° F. from 0 to 50 per cent relative humidity.

g. Air horsepower. The horsepower output of an air-moving device is known as "air horsepower." It is easily estimated by the formula:

$$\text{AHP} = \frac{(\text{c.f.m.})\ (h)}{6350}$$

where AHP = horsepower, c.f.m. = cubic feet of air per minute, and h = pressure in inches of water.

Air horsepower is sometimes further qualified as either "total air horsepower" or "static air horsepower." Either of these may be computed from the above equation by using for head (h) the "total pressure" or "static pressure," respectively. The choice between these two methods of rating must depend on whether the over-all fan efficiency is to be expressd as "total efficiency" (also called "mechanical efficiency"), or "static efficiency," inasmuch as fan manufacturers use either or both in their detailed statements of performance.

2. Ejectors, Venturi Ejectors, or Syphon Jets

The venturi ejector is a low-efficiency air-moving device selected as a last resort when the ventilating system must handle excessive temperatures, corrosive gases, flammable vapors, or viscous or sticky air contaminants that would quickly destroy the effectiveness of axial or centrifugal fans. The air-moving efficiency is highly sensitive to the physical proportions of the outer conduit, and the location of, and air velocity through, the inner jet. Both straight-tube and venturi-type conduits are used, but the latter can be made more efficient. Efficiencies range from 5 to 20 per cent.

Designers who are in a position to compute and specify a high-quality ejector on the basis of the best available aerodynamic data are referred to the comprehensive treatment prepared by McElroy.[19] Less precise information has been offered by other writers, which is satisfactory for applications where high jet velocities can be produced (8000 to 10,000 l.f.m.) and where one is reconciled to efficiencies in the range of 5 to 10 per cent. The "straight-tube" ejector with a jet diameter one sixth of the straight duct diameter can be used with reasonable success when the connected system has a very low resistance, less than $^1/_4$ inch of water.

V. Design of Ducts for Exhaust Systems

Many special forms and charts have been created and published for the purpose of facilitating the aerodynamic design of ductwork for ventilating systems. Unfortunately, some of these devices consume more time than they save, particularly if the designer or estimator is not in constant practice.

No single form or procedure is offered here as superior to all others, but instead the reader is advised to adopt one that best suits his requirements. If exhaust-system calculations are infrequent, special tabulating and computing forms are less important than a complete list of individual steps for the essential mathematical operations.

A plan of design sequence is now outlined, and this is followed by a brief example of its application.

A. PROCEDURE FOR DESIGN OF EXHAUST SYSTEMS

Lay Out the Ductwork and Design the Hoods

1. Prepare a sketch or layout of the exhaust system; use single lines for ducts if simplicity is desired. The layout is more helpful if approximately to scale, although subsequent steps in calculating duct sizes can be carried out even with a very poor drawing.

2. Select the type of hood that will do the best possible job with the smallest amount of

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[19] G. E. McElroy, *U. S. Bur. Mines Tech. Paper* No. **678,** 1945.

air flow. This requires ingenuity in designing enclosures that will not interfere with production, or hoods with movable sections that can and will be operated as planned. There is no point in creating an "ideal" hood that cannot be used without seriously disrupting the production schedule, inasmuch as neither worker nor employer will tolerate its use.

Determine Air-Flow Rates for Each Exhaust Hood

3. Estimate the control or "capture" air velocity required for each operation and type of hood or enclosure. Tables 8, 9, and 10 suggest control velocities. This part of the design process involves a great deal of judgment.

4. Compute the boundary area of the *plane*, *cylinder*, or *sphere* of influence through which the selected "capture" velocity must operate. The ability to conceive hood arrangements in three dimensions is an advantage.

5. Compute the total air flow in c.f.m. for each hood (capture velocity times area of influence) and put this rate on the sketch or diagram of the system for reference purposes.

6. Summarize the air flow for each section of the branch and main ductwork on some form or preferred calculation sheet, or enter the air flows directly upon the diagram or drawing.

Establish Air Velocities for Each Duct Section

7. Select the minimum effective transport velocity for particulate matter (Table 15). For transporting of gases and vapors, duct velocities can be as low as is consistent with space and weight limitations. Velocities in the range of 1000 to 2000 l.f.m. for gases and vapors are the usual compromise between excessive duct size and unnecessarily high air-horsepower requirements.

8. Figure the nearest practical duct diameter to carry the required c.f.m. at the proper velocity. Consideration should be given to the sheet metal fabricator's standard size increments to avoid unnecessary additional expense. If the available duct sizes are much different from the theoretically required diameters, compute the actual transport velocity for use in subsequent design steps.

Determine the Entrance or Orifice Loss for Each Hood

9. Compute the velocity pressures corresponding to the air velocities in each branch duct connected to an exhaust opening (see page 337).

10. Estimate the orifice loss for each hood in percentage of velocity pressure in the branch pipe (see Figure 19).

11. Compute from items 9 and 10 the entrance losses in terms of inches of water.

Determine Duct Friction and Transition Losses

12. Compute the losses in elbows, branch to main connections, or other transitions either (*a*) in terms of equivalent straight-pipe diameters (Figures 20 and 21) or (*b*) in terms of velocity pressures, whichever form corresponds with the data at hand. The equivalent straight-pipe method has the advantage that such transition losses can be added directly to the straight-pipe sections for use with friction charts. The velocity-head method may be preferred by those who are especially familiar with the fundamentals of fluid mechanics.

13. Obtain the duct friction losses from a chart, table, or formula, whichever you prefer to use. Figure 22 is used at this point.

Balance the Pressure Drop by Adjusting Duct Sizes

14. Summarize the losses for each branch to determine where to increase or decrease the duct sizes to obtain better balance of pressure drop. (This assumes that balancing will not be left exclusively to manually operated dampers.) The total pressure drop from any points in the system to each upstream opening or exhaust hood should be the same, if balance is to be achieved. This is so because in actual operation, the air-flow quantities through all open branches automatically adjust themselves to fulfill this requirement of balance. If the flow

TABLE 15

Air Velocities for Transporting Various Dusty Materials
(Linear feet per minute)

Material	Dust collecting		Pneumatic conveying	
Aluminum dust	4500	6000	—	—
Asbestos	3000	3500	—	—
Ashes, ground	—	—	6000	8500
Bakelite molding powder	2500	3500	—	—
Barley	—	—	5000	6500
Buffing lint	3000	5000	—	—
Cast-iron dust	4000	5000	—	—
Cement	3500	4000	6000	9000
Clay	3500	4000	—	—
Coal, powdered	3500	4000	4000	5500
Cocoa	3000	3500	—	—
Coffee beans	—	—	3500	5000
Cork, ground	2500	3000	3500	5500
Corn	—	—	5000	7000
Cotton	2500	3000	4000	6000
Cottonseed	—	—	4000	6000
Flour	2500	3500	4000	6000
Foundry dust	3500	5000	—	—
Grain dust	2500	3500	—	—
Granite dust	4000	5000	6000	8000
Grinding dust	3500	5000	—	—
Ground feed ($^1/_2$-in. screen)	—	—	4500	6000
Hemp	—	—	4500	6000
Hog waste	3500	4500	4500	6500
Jute butts	—	—	3500	5000
Jute dust	3000	3500	—	—
Jute lint ("flyings")	2500	3000	—	—
Lead dust	4000	5000	—	—
Leather dust	3000	4000	—	—
Lime	3500	4000	5000	7000
Magnesium dust	4500	6000	—	—
Metal turnings	4000	6000	5000	8000
Oats	—	—	4500	6000
Pulp chips	—	—	4500	7000
Rubber dust	2500	4000	—	—
Rye	—	—	5000	7000
Salt	—	—	5500	7500
Sand or silica	3500	4500	6000	9000
Sawdust, light or dry	2500	3000	4000	6000
Sawdust, heavy or wet	3000	5000	—	—
Soap dust or powder	3000	3500	—	—
Sugar	3000	3500	5000	6000
Tanbark, dry	—	—	4500	7000
Tanbark, damp or leached	—	—	5500	7500
Wheat	—	—	5000	7000
Wood blocks (edgings)	3500	5000	4500	6000
Wood flour (sander dust)	2500	3000	4000	6000
Wool fibers	3000	4500	4500	6000

through any branch is too high, further closing of a damper increases the friction or energy loss through that branch; this makes it possible for a smaller volume of air flow to create the necessary pressure drop for a condition of balance.

15. If necessary, after the system is balanced on paper to a reasonable degree by adjusting the round duct sizes, conversion to rectangular duct sizes can be made by using Figure 23

Summarize the System Resistance

16. Determine the adjusted total pressure drop of the branch and main duct system by adding the pressure losses beginning with any one exhaust opening and proceeding toward the fan or dust collector. Remember that so long as the branch duct system has been reasonably balanced in accordance with item 14 above, it will be a simple matter to select the safest starting point for totaling the pressure losses. However, if no balancing is attempted, then the losses must be estimated for the single run of duct that you *believe* will have the greatest total resistance. Experienced designers after a few moments of inspection usually can determine the "longest run" in terms of friction loss. In this case the "longest run" implies the course that offers the greatest resistance to air flow, and not necessarily the one longest in terms of feet.

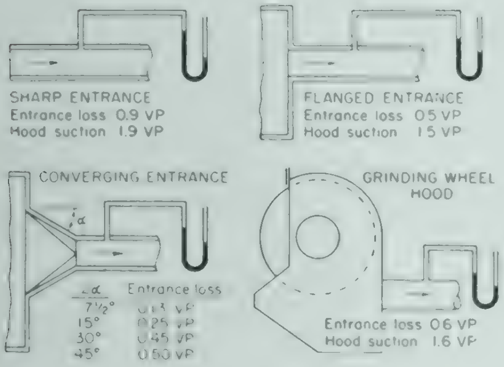

Figure 19. Exhaust hood entrance losses in relation to velocity pressure (VP). (Courtesy American Air Filter Co., Louisville.)

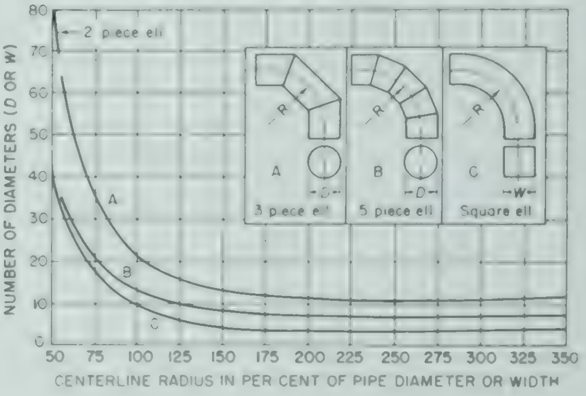

Figure 20. Pipe-elbow friction losses in terms of pipe diameters. (Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1950,* Chapter 31.)

17. Add the resistances of accessory equipment such as air cleaners, weather caps, and shutters. Since this type of equipment varies greatly in resistance to air flow, manufacturers' data should be consulted.

Select an Appropriate and Adequate Fan or Air Mover

18. From the total air flow in c.f.m. and the total system resistance or S.P. in inches of water, select from manufacturers' catalogs a fan of the type, size, and speed to give the highest operating efficiency or lowest H.P. consistent with other considerations, as outlined on pages 326–338. Note that the total resistance of the system does not include the velocity pressure at the entrance to the exhaust hoods.

B. DESIGN EXAMPLE

Figure 24 is a line diagram of a simple grinding exhaust system that has been aerodynamically designed according to the plan outlined above. The results are summarized in Table 16.

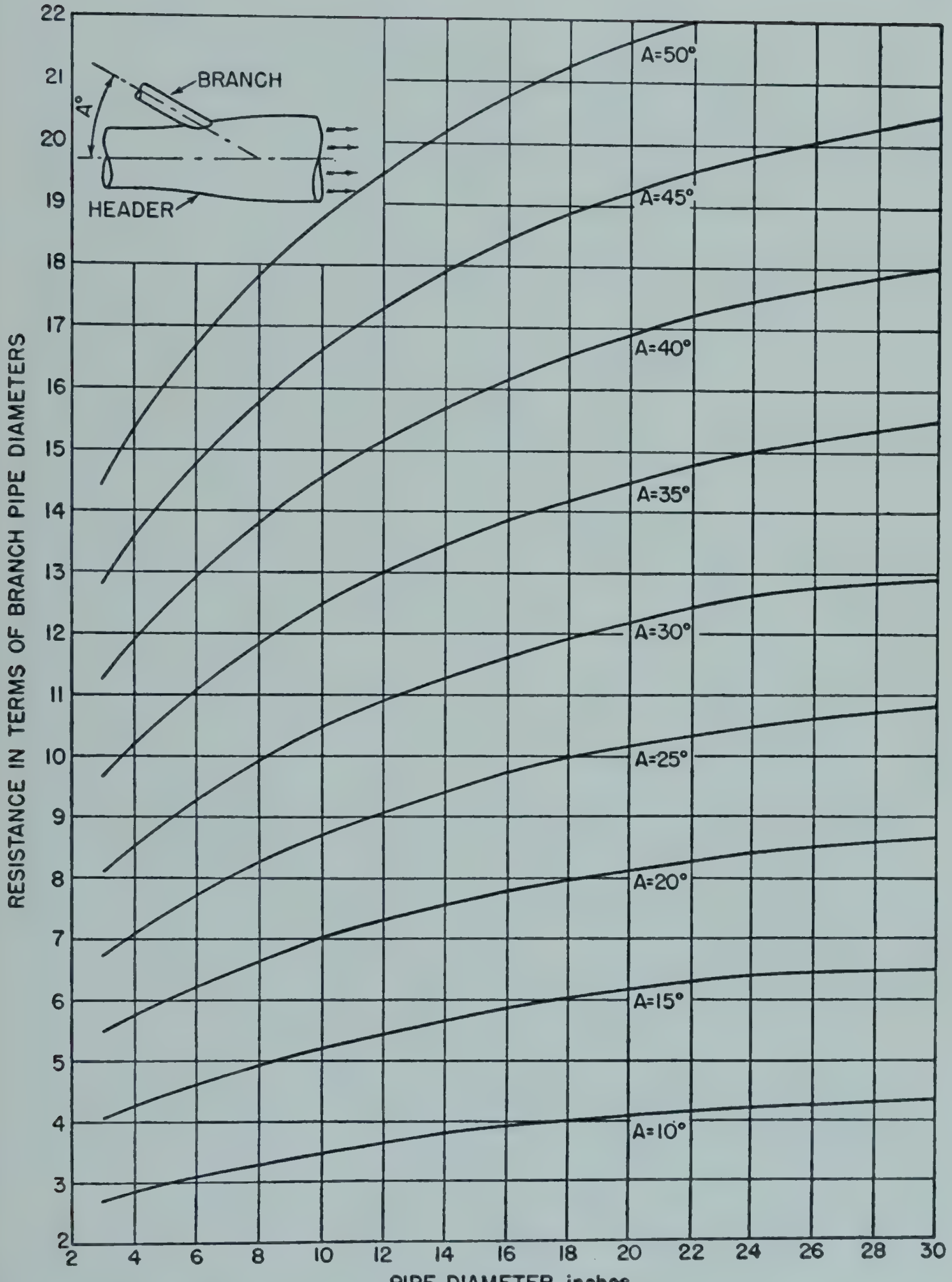

Figure 21. Branch pipe to main duct transition losses in terms of pipe diameters.[18]

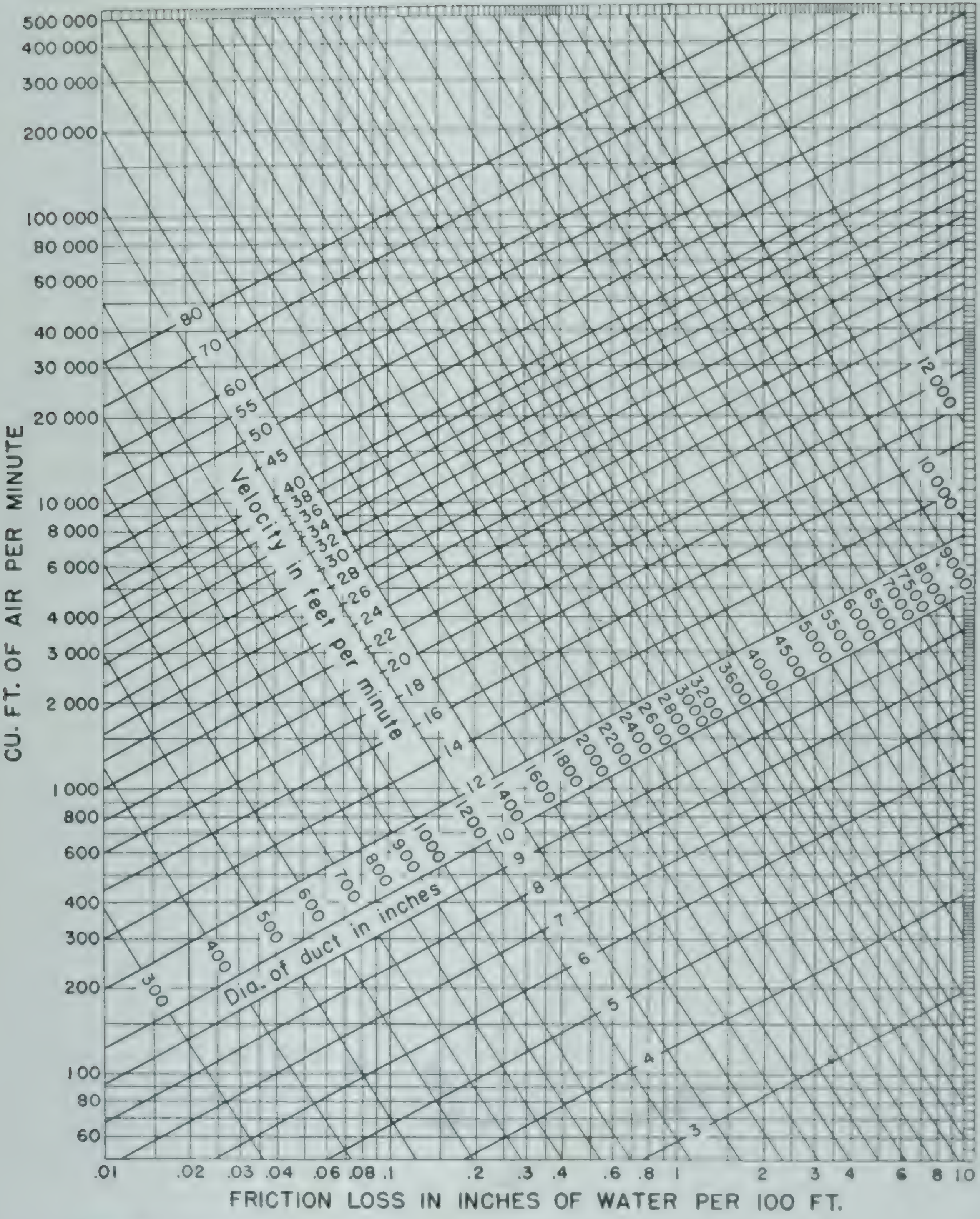

Figure 22. Friction chart for air flow through round galvanized sheet-metal ducts of average construction with about 40 joints per 100 feet based on dry air at 29.92 inches barometric pressure and 70° F. (Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1949*, Chapter 41.)

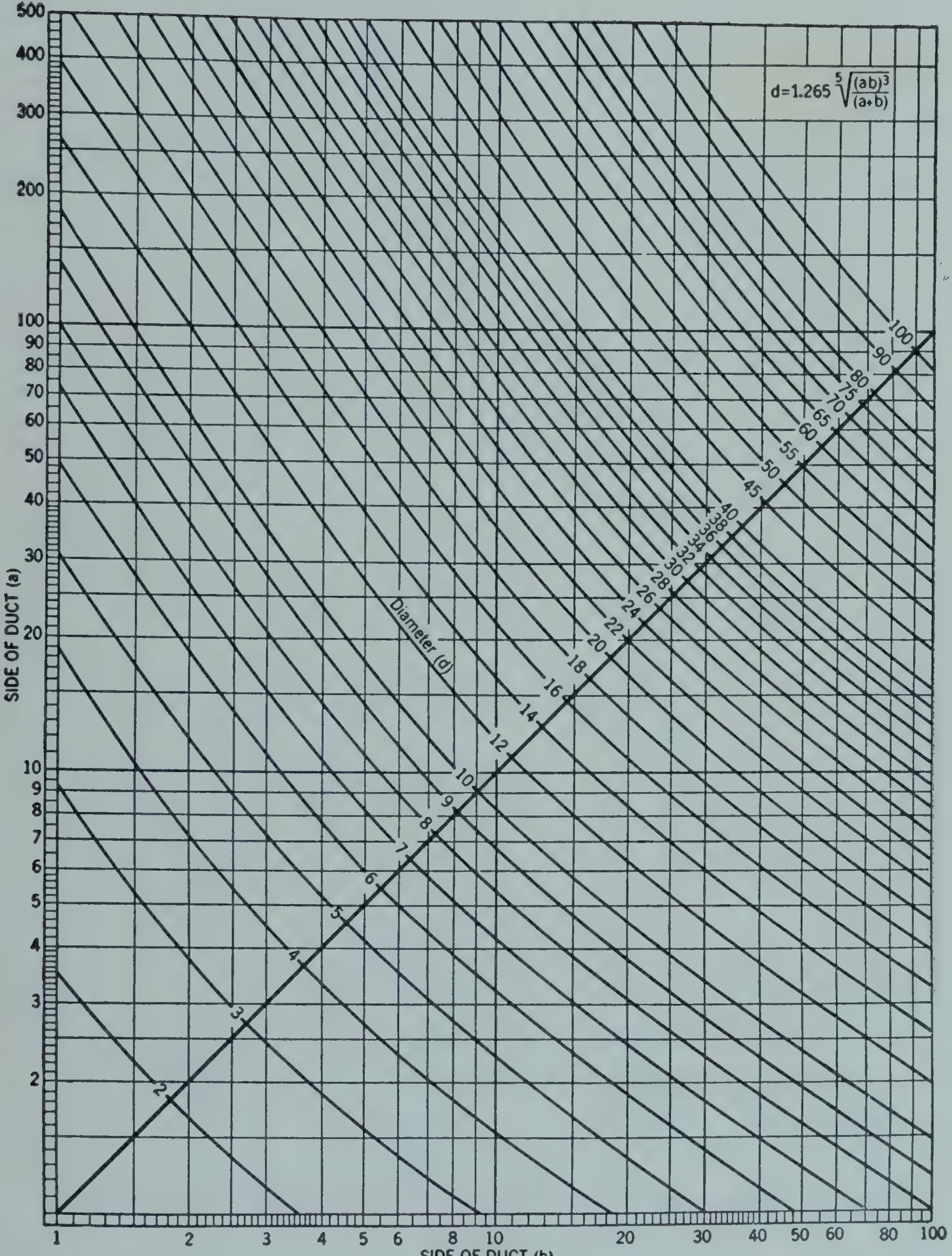

Figure 23. Chart for converting round to rectangular duct sizes having equivalent friction losses. (Reprinted by permission from *Heating, Ventilating, Air Conditioning Guide, 1948*, Chapter 41.)

TABLE 16

Calculation of Exhaust System Pressure Losses								Summary of Losses					
			From friction chart										Corrected
Hood and duct section	C.f.m. through duct section	Average design velocity (l.f.m.)	Nearest duct diam. (in.)	Actual duct vel. (l.f.m.)	Friction/ 100 ft. (in. H_2O)	Total equiv. straight duct (ft.)	Total friction (in. H_2O)	Hood	A	B or C	D	E	E
								V.P.	1.05	0.77	0.86	0.90	1.21
								% loss	50	60	60	50	50
								In. H_2O	0.53	0.46	0.52	0.45	0.61
A-1	800	4000	6	4100	4.3	15	0.65	—	0.65	—	—	—	—
B-2	300	4000	4	3500	5.1	19	0.97	—	—	0.97	—	—	—
C-3	300	4000	4	3500	5.1	19	0.97	—	—	—	—	—	—
4	1400	4000	8	4000	2.9	20	0.58	—	0.58	0.58	—	—	—
D-5	600	4000	5.5	3700	4.0	31	1.24	—	—	—	1.24	—	—
6	2000	4000	9.5	4100	2.5	10	0.25	—	0.25	0.25	0.25	—	—
E-7	1000	4000	7	3800	3.0	34	1.02	—	—	—	—	1.02	—
E-7 corrected	1000	—	6.5	4400	4.5	33	1.49	—	—	—	—	—	1.49
8	3000	4000	12	3800	1.6	15	0.24	—	0.24	0.24	0.24	0.24	0.24
Subtotal for Balancing Purposes:									*2.25*	*2.50*	*2.25*	*1.71*	*2.34*
										2.00	*dust collector*		
9	3000	3000	14	2800	0.75	19	0.14	—	—	0.14	—	—	—
10	3000	2000	16	2200	0.39	30	0.12	—	—	0.12	—	—	—
Total Resistance of System Using Maximum Branch Resistance:										4.76			

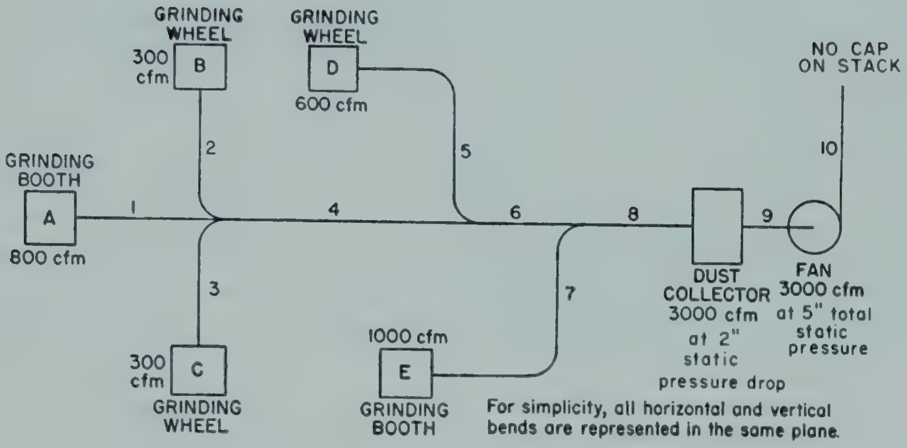
GRINDING WHEEL
300 cfm
B
GRINDING WHEEL
D
600 cfm
NO CAP ON STACK
GRINDING BOOTH
A
800 cfm
1
2
3
4
5
6
7
8
9
10
DUST COLLECTOR 3000 cfm at 2" static pressure drop
FAN 3000 cfm at 5" total static pressure
1000 cfm
E
300 cfm
C
GRINDING WHEEL
GRINDING BOOTH
For simplicity, all horizontal and vertical bends are represented in the same plane.

Figure 24. Line diagram of an exhaust system.

C. RELATION BETWEEN AIR VELOCITY AND VELOCITY PRESSURE

The dynamic or kinetic energy of moving air may be expressed in terms of the equivalent static or potential energy of a vertical column of water. Thus, the downward pressure exerted by a column of water 1 inch high is enough to balance the pressure created by an air stream that impinges against a stationary surface with a velocity of approximately 4000 l.f.m. We say, therefore, that 4000 l.f.m. has a "velocity head" or "velocity pressure" of 1 inch of water. Conversely, if air under a pressure of 1 inch of water is allowed to escape to the atmosphere through a frictionless orifice, it will emerge with a velocity of 4000 l.f.m.

For most applications in the field, the following approximate formula can be used in either of the two forms given:

$$\text{Air velocity, or } V = 4000\sqrt{VP}$$

$$\text{Velocity pressure, or } VP = (V/4000)^2$$

D. AIR-DUCT FRICTION

The friction chart (Figure 22) applies to the flow of dry air at 70° F. and 29.92 inches Hg barometer through round straight galvanized sheet-metal ducts of average construction with about 40 slip joints per hundred feet.

Friction losses in pipes or ducts that differ considerably from the conventional sheet-metal construction can be computed from the following formula in combination with Tables 17 and 18:

$$\frac{\text{inches of water}}{\text{hundred feet}} = f\left(\frac{1200}{\text{diameter in inches}}\right)\left(\frac{\text{l.f.m.}}{4000}\right)^2$$

The procedure is to: (*1*) select an appropriate roughness measure (ϵ) from Table 17; (*2*) compute relative roughness, ϵ/D, in which D is pipe diameter in feet; (*3*) compute Reynolds Number from formula on page 339; (*4*) use Reynolds Number and relative roughness in Table 18 to find the friction factor, f; (5) use f in the equation above to find the air-flow friction loss in inches of water per hundred feet of pipe.

TABLE 17

Roughness Measure (ϵ) for Various Kinds of Pipe[20]

Kind and condition of pipe	ϵ (ft.)
Perfectly smooth drawn tubing	0.0000015
Commercial steel or wrought iron, new	0.00015
Asphalted cast iron	0.0004
Galvanized iron (used for Figure 22)	0.0005
Cast iron	0.00085
Concrete, average roughness	0.003
Riveted steel, very rough	0.01

TABLE 18

Friction Factors (f) Based on Reynolds Number and Pipe Roughness[20] for Use with Friction Formula Above (page 337)

Relative roughness,[a] ϵ/D	Reynolds Number 10^4 10,000	 10^5 100,000	 10^6 1,000,000	 10^7 10,000,000
0.00001	0.030	0.018	0.012	0.009
0.0001	0.031	0.0185	0.0135	0.012
0.0005	0.032	0.0205	0.0175	0.017
0.001	0.032	0.022	0.020	0.0195
0.005	0.038	0.031	0.030	0.030
0.01	0.043	0.038	0.038	0.038
0.03	0.060	0.057	0.057	0.057
0.05	0.074	0.072	0.072	0 072

[a] ϵ = roughness measure of pipe surface in feet and D = inside diameter of pipe in feet.

For kinds of pipe not listed in Table 17 the roughness measure can be selected for the material most likely to be similar in surface characteristics. In estimating the internal pipe roughness, consideration should be given to surface treatment of the pipe for corrosion resistance, and the possibility of surface modification by the accumulation of particulate matter, especially if hygroscopic or unusually electrostatic.

E. REYNOLDS NUMBER

The Reynolds Number used in fluid mechanics and required in the use of Table 18 is a "dimensionless" figure that may be computed from the following equation:

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[20] L. F. Moody, *Trans. Am. Soc. Mech. Engrs.*, **66**, 671 (1944).

$$\text{Reynolds Number} = \frac{(\text{velocity in f.p.s.})\ (\text{diam. in ft.})}{(\text{kinematic viscosity in sq. ft./sec.})}$$

A convenient, approximate form that applies to most air-flow conditions in ventilating systems, and is adjusted to the conventional units, is the following:

$$\text{Reynolds Number} = 8.5\ (\text{l.f.m.})\ (\text{diam. in in.})$$

The constant 8.5 in this equation is based on a kinematic viscosity for air at 70° F. and 29.92 inches Hg barometer of 0.000163 sq. ft. per second. For values of kinematic viscosity at high and low temperatures and high pressures, see the convenient chart presented by L. G. Miller.[21]

F. FLEXIBLE METAL, CANVAS, OR RUBBER DUCTS

The friction of air flow through flexible ducts is considerably higher than for straight sheet-metal pipes. If the inside surface is deeply corrugated, the friction loss may be two to four times the loss for smooth pipe of equal diameter. Furthermore, it is necessary to anticipate increased friction loss to a degree depending upon the amount of curvature to which the duct can or will be subjected.

Not all flexible ducts should be treated as unusually high-resistance material. Some natural or synthetic rubber ducts are so constructed that the inside is relatively smooth, while the corrugations due to metal reinforcement appear on the outside surface. Also, some metal flexible ducts are so rigidly constructed that sharp curvature is impossible. Field tests of friction loss should be made if its effect on air flow or power consumption is of serious consequence.

G. ADJUSTABLE DAMPERS OR FLOW REGULATORS

The tendency still exists to install in each branch of an exhaust or ventilating system some type of damper to make possible an initial or periodic variation in the amount or distribution of air flow. This practice has reached the ultimate in disfavor in connection with the handling of highly explosive dusts that may collect or settle out in the vicinity of dampers as a result of eddies or sudden changes of flow direction. A great many objections to dampers have been expressed among designers of exhaust systems, but the fact remains that in many cases their use has made possible the correction of air-flow distribution when the original design did not succeed in anticipating the best proportion of ventilation for each machine or process in the system. It is true that tremendous power has been wasted throughout the years by the work of dragging air through the constrictions imposed by dampers, and efforts to improve the accuracy of ventilation estimates and designs must be encouraged. Likewise, some attention must be given to the design of better flow-regulating devices to give the user the flexibility his operations may demand. Designs also can be, and have been, made to permit adjustments that cannot be disturbed by unauthorized persons without obvious damage or destruction.

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[21] L. G. Miller, *Trans. ASHVE,* **43,** 71 (1937).

H. PNEUMATIC CONVEYING SYSTEMS

Light bulky materials, such as wood shavings, textile fibers, paper trimmings, ground cork, and grain products, can be transported by air without excessive power requirements and without damage to the materials or conveying equipment. Conveying velocities may be of the same order as for dust-handling systems, or they may be much higher, as indicated in Table 15, with resultant increase in the power requirement. The quantities of air required for pneumatic conveying vary approximately from 100 cu. ft. per pound of light fluffy material such as "open cotton" at 3000 l.f.m. to about 25 cu. ft. per pound of heavy solid materials at 8000 l.f.m.

I. CONSTRUCTION SPECIFICATIONS FOR VENTILATING SYSTEMS

The designer should obtain the codes and standards that apply to his industry, state, or trade association to be certain that his preferences do not conflict with locally established practice. It is not possible to formulate a list of specifications that will have nation-wide acceptance without removing most of the details that would be of interest. Furthermore, construction materials, methods, and standards are improving yearly.

The annual *Guide* of the American Society of Heating and Air-Conditioning Engineers is suggested as a source of information on construction features that will be kept reasonably up to date by the frequent revisions prepared by authorities among the Society's membership. The Committee on Industrial Ventilation of the American Conference of Governmental Industrial Hygienists has published a loose-leaf reference book incorporating the recommendations of industrial hygiene engineers on construction and use of ventilating systems. Among state codes, the most widely publicized in the field of industrial ventilation are those prepared by the Division of Industrial Hygiene of the New York State Department of Labor. The American Standards Association's list of approved and adopted codes on ventilation is already substantial and continues to grow. It is an increasingly important source of technical and design information, as professional organizations assemble their material for submission to the ASA.

J. MAINTENANCE OF VENTILATING EQUIPMENT

Too frequently the designer has no further control over the ventilating system after it is placed in use. Whether he made provisions for alterations and additions, or issued instructions that no change must be made without a review of the design, the fact remains that sooner or later something will be done to upset the original plan, and place new burdens upon the fan, collector, and ductwork for which they were never prepared. Accordingly, the alert redesigner or investigator will proceed with caution when appraising the original design.

Innumerable failures in mechanical ventilation are due to inadequate care or maintenance, and this applies to nearly every part of the system, whether movable or stationary. When it is realized that contaminated air is in constant motion through the hoods, ducts, cleaners, and fan, it is readily appreciated that the entire air-handling equipment should be classified as dynamic rather than static. Transparent ducts would settle this point beyond doubt in many cases.

Perhaps the best assurance that mechanical ventilation is functioning properly is a scheme of periodic inspection and testing. Volume III outlines the practical methods of observing and measuring air flow. Successful maintenance departments have learned to use these reliable methods of measurement to ensure first-class performance.

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CHAPTER XI

Respirators and Respiratory Protective Devices

FRANK A. PATTY

I. Historical Résumé and Present Approval Procedure

A respirator is defined as a device covering the mouth or nose, to prevent the inhalation of noxious substances. The oldest record we have of the use of such a device is that given in the first century A.D. by Pliny the Elder, who wrote of minium refiners wearing bladders over their faces to avoid inhaling mercury-bearing dust. Gas masks, oxygen-supplying apparatus, and hose masks (diving helmets) were introduced into Europe during the nineteenth century but they did not come into general industrial use until after World War I. Oxygen-breathing apparatus was introduced into the United States about 1907. Its first general usage came in 1910 with its adoption for mine-rescue work. The canister gas mask was introduced into this country when the United States Bureau of Mines was assigned the problem of developing a military mask for the American soldiers in 1917. This work later grew into the Research Division of the Chemical Warfare Service. A good serviceable mask for war uses was developed, and at the end of the war, work was continued by the Bureau with a view toward the development of an industrial mask.

Many of the military masks of the acid-gas and organic-vapor type were thrown on the market by salvage dealers after the war, but were used by returning soldiers for protection against all gases. This error was encouraged by some of the dealers who made extravagant claims concerning the masks. As a result there were many poisonings, mainly nonfatal, around ammonia refrigerating plants and among fire fighters who were exposed to carbon monoxide. The alarm caused by these poisonings produced an extensive educational campaign through newspapers, the technical press, and personal instruction. Research gradually developed canisters for various gases, and the universal canister that protects against all common gases or combinations of gases. The next step was the development of the hose mask, which is simple and foolproof, and which offers respiratory protection in any situation that can be reached by 150 ft. of hose.

In each instance, however, personal respiratory protective apparatus that really offered dependable protection was not made available in the United States until the United States Bureau of Mines set up approval schedules and procedures for permissibility tests. These schedules[1] are revised from time to time to conform with advances in research and development. It was not until 1935 that effective dust respirators became available to American industry, when the first respirator passed the official schedule of tests. Scores of inferior, and in many instances useless, devices were discarded after these tests demonstrated their unsatisfactory performance.

These tests now cover oxygen-breathing apparatus, canister gas masks, hose masks, abrasive-blasting and other air-line respirators, filter-type dust respirators, and chemical cartridge respirators. The tests specify the minimum permissible performance and the maximum permissible resistance to inhalation and exhalation. Certificates of approval issued by the Bureau for the accepted devices are the basis for all lists of approved industrial respiratory protective equipment published by any agency in the United States. No data are published enabling the public to choose the respirator giving the best performance, but lists of all devices meeting the minimum requirements are published. However, these requirements are raised occasionally to keep pace with the more progressive manufacturers, and holders of early approvals are encouraged to improve the performance of their devices to meet these higher standards in order to retain the approval label. Nominal fees charged for approval testing vary with the time required for men to perform the scheduled tests. All approved devices are stamped with an approval label or number, such as BM-1400, in which the first two digits of the number refer to the schedule of tests under which the device was approved, and the last two are specific for the particular device.

II. Types and Uses of Respiratory Protective Devices

Respiratory protective devices are used to supplement other methods of control and are more frequently used as an emergency measure. Respiratory protection against all classes and combinations of air contaminants is available under two general classifications: (*1*) air-purifying respirators, which purify the air by removal of the contaminant, and (*2*) atmosphere-supplying respirators, which supply respirable, uncontaminated air or oxygen to the wearer.

A. AIR-PURIFYING RESPIRATORS

Air-purifying respirators provide protection only by removing specific contaminants from the atmosphere. Obviously, sufficient oxygen must already be present in the atmosphere to support life.

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[1] Self-contained breathing apparatus, *U. S. Bur. Mines, Schedule* **13C** (1946). Gas masks, *U. S. Bur. Mines, Schedule* **14F** (1955). Filter-type dust, fume, and mist respirators, *U. S. Bur. Mines, Schedule* **21A** (1955). *Supplied-air respirators, U. S. Bur. Mines, Schedule* **19B** (1955). Nonemergency gas respirators, *U. S. Bur. Mines, Schedule* **23A** (1955).

1. Gas Masks (Canister Type)

A canister gas mask usually consists of a full facepiece connected by a flexible breathing tube to a canister containing materials for purifying the air, and equipped with a suitable supporting harness. A check valve in the canister and an exhalation valve in the facepiece control the direction of flow of air through the device. The air-purifying materials in the canister vary with the type of canister, since no one substance will remove all contaminants. Alkaline materials such as Caustite and soda lime combine with and remove any of the acid gases except nitrogen oxides; silica gel and activated carbon adsorb organic vapors; ammonia is removed by various materials, such as silica gel adsorbent or some other substance that has been impregnated with copper or cobalt salts to combine with the ammonia; while carbon monoxide is catalytically oxidized to carbon dioxide by Hopcalite, a trade preparation of manganese and copper oxides. Filters may be provided within the canister for removal of particulate matter. The protection that a canister provides determines its type, and depends upon the material with which it is filled. It may be for a single gas, one or more classes of gases, or for all gaseous contaminants. The types of canisters are designated by letters and a color code, as listed in Table 1.

TABLE 1

Color Code for Canisters

Canister type	Contaminants to be protected against	Color
A	Acid gases	White
B	Organic vapors	Black
C	Ammonia	Green
D	Carbon monoxide	Blue
AE, BE, etc.	Dusts, fumes, mists, fogs, and smokes in combination with any of the above gases or vapors	$^1/_2$ in. contrasting black or white stripe (on the respective color)
AB	Acid gases and organic vapors	Yellow
ABC	Acid gases, organic vapors, and ammonia	Brown
N	All of the above atmospheric contaminants	Red

The canister gas mask is emergency equipment and is not suitable to wear for prolonged periods of work, because of discomfort and fatigue due to the resistance to inhalation and exhalation. This type of respirator is approved for use in concentrations of acid gases and organic vapors up to 2 per cent by volume, and in up to 3 per cent ammonia. The service life of a canister depends upon the concentration of gas encountered, the volume of air inhaled by the wearer, the characteristics and amount of the chemical absorbents, and other factors. Obviously the universal type of canister must be filled with a variety of materials in order to protect against practically all gaseous contaminants. For protection against a single known gas, or class of gases, a single-absorbent type of canister is preferable in that it has a longer life and provides more economical protection. The useful life of the universal, type N, canister is limited by the life of the drying agents used to protect the catalyst from moisture (2 to 6 hours). Figure 1 diagrams a typical type N canister. The continued use of a partially exhausted

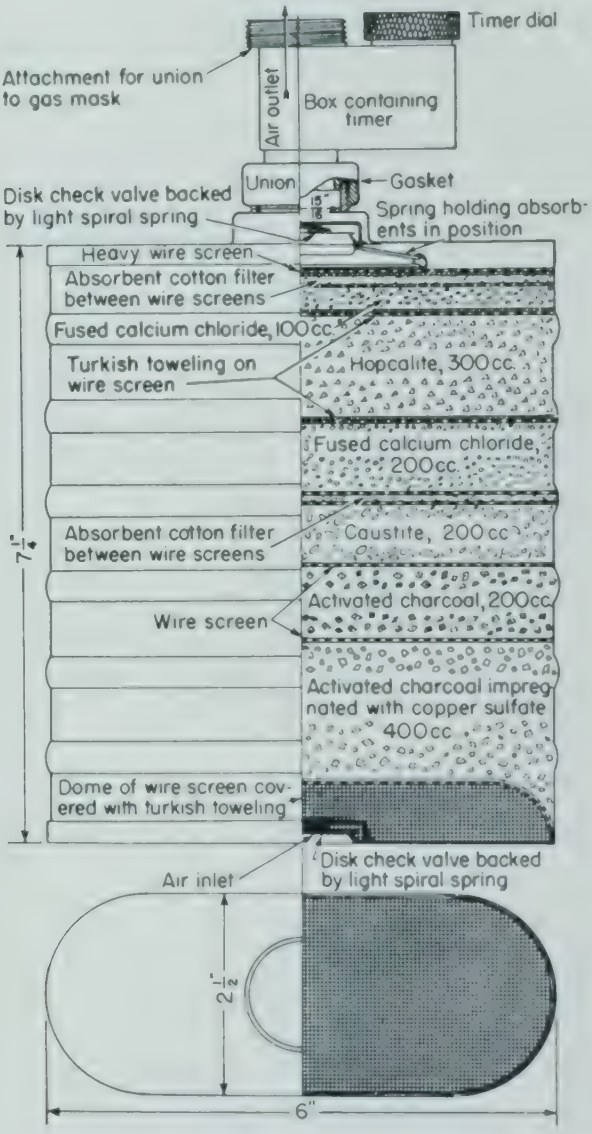
Timer dial
Attachment for union to gas mask
Air outlet
Box containing timer
Union
Gasket
15"/16
Disk check valve backed by light spiral spring
Spring holding absorbents in position
Heavy wire screen
Absorbent cotton filter between wire screens
Fused calcium chloride, 100cc.
Turkish toweling on wire screen
Hopcalite, 300cc.
Fused calcium chloride, 200cc.
Absorbent cotton filter between wire screens
Caustite, 200cc
Activated charcoal, 200cc
Wire screen
Activated charcoal impregnated with copper sulfate 400cc
Dome of wire screen covered with turkish toweling
7½"
Air inlet
Disk check valve backed by light spiral spring
2½"
6"

Figure 1. A type N canister. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

canister may be permissible in gases or vapors having distinct warning characteristics, provided it is used near an uncontaminated area so that the wearer may reach safety quickly after detecting leakage, because the end of the useful period is not sharp, but rather gradual. Any used canister should always be replaced with a new one before the mask is used in an unusually hazardous situation.

2. Chemical Cartridge Respirators

Chemical cartridge respirators usually consist of a small canister attached directly to a half-mask facepiece. The fills are similar to those used in gas masks, and in fact these respirators may be considered miniature gas masks. Filters for removing particulate matter may be incorporated. These respirators are designed for prolonged use in light exposures where workmen could work without protection, but where prolonged daily exposures might prove harmful to health. The maximum concentration of gases or vapors for which such devices are approved is 1000 p.p.m., 0.1 per cent by volume. Only a relatively few chemical cartridge respirators have been granted approval certificates, and the protection afforded by some of the unapproved articles is open to question. Recently, cartridge respirators have been approved for use against solvent vapors. A word of caution should be given, however, that these do not protect against lead mists, often associated with solvent vapors in paint spraying. Where lead mists are involved no cartridge respirator is approved, nor should any be depended upon; until further advances are made some air-supplying device is required. Respirators approved for removal of lead mists as well as solvent vapors and mists have not yet appeared.

3. Mechanical Filter Respirators (for Dust, Fume, Fog, or Mist)

Mechanical filter respirators usually consist of a fibrous filter, such as felt or specially treated cellulose fiber paper, secured in a holder and connected directly to a half-mask facepiece. The filter is a maze of fine, closely packed fibers that form a network of microscopic passages. When air is drawn through this maze, the major part of the suspended dust, fume, mist, and fog is removed by physical trapping. These filters are approved for various uses, but not all of them are suitable for every purpose. Filters approved for silica dusts, however, are suitable for all fibrosis-producing and nuisance dusts. Filters approved for mechanically generated lead dusts are suitable for other mechanically generated dusts: toxic, fibrosis-producing, or nuisance. None of these is suitable for metal fumes which, owing to their smaller particle size, require a finer mesh filter. Fumes, it must be understood, are particulate matter formed by volatilization and condensation, as for instance in lead burning, and must not be construed to be gases or vapors. A filter suitable for metal fumes will filter out any particles for which any mechanical filter is approved. Unlike the gas mask, the mechanical filter improves in filtering efficiency with use or plugging. Increased breathing resistance is the factor that limits this filter's life. These devices are intended for prolonged use and therefore are light in weight and compact. They do not seriously interfere with most ordinary duties. To say that they are comfortable is stretching the imagination, and where control by other means is feasible, control by personal respiratory protection is not the method of choice. Rather, mechanical-filter respirators are to be considered as either temporary or last-resort measures; but they certainly are to be recommended for any workman who is obliged to work in an atmosphere significantly contaminated by dust, fumes, fogs, or mists, especially if the contaminant is recognized as harmful to health. Approval procedures for radioactive dusts are being considered, but as yet procedures have not been scheduled for dusts more toxic than lead.

B. ATMOSPHERE-SUPPLYING RESPIRATORS

Atmosphere-supplying respirators are independent of the wearer's atmospheric environment, and they offer protection in any atmosphere successfully withstood by the skin. There are two classes: one supplies air through a hose or tube, and the other is a self-contained type in which either a compressed oxygen or air supply is carried by the wearer or oxygen is generated as required.

1. *Supplied-Air Respirators*

Air-supplying respirators are further divided into three classes: hose masks, air-line respirators, and abrasive-blasting respirators.

Hose Masks. Hose masks, type A supplied-air respirators, consist of a full facepiece, a harness, a 1-inch (inside diameter) noncollapsible hose line securely fastened to the harness, and connected by a breathing tube, or tubes, to the facepiece, and a hand-operated blower. The harness and hose are strong enough to be used to retrieve the wearer in an emergency, and the approved hose length is from 25 to 150 ft. The reason for requiring a hand-operated, rather than a motor-operated, blower is the additional safety factor of having a second man present in the event of any difficulty. The hose, blower, and check valve are such that the wearer can breathe without encountering excessive resistance to air flow, even though the blower is not operated: as for instance during the short time required to escape to pure air, if the second man should stop operating the blower. The blower intake must be located in uncontaminated air and, since the maximum approved length of hose is 150 ft., the device cannot be used more than that distance from respirable air. Air is supplied to the mask at a pressure equal to the very slight resistance of the exhalation valve, and therefore there is no resistance to inhalation while the blower is operating. A hose mask may be worn for a greater length of time without fatigue than can a canister gas mask. Type A hose masks are designed to be worn in atmospheres that are immediately dangerous to life, and to afford respiratory protection in all types of atmospheric contaminants, as well as in atmospheres deficient in oxygen.

Special hose masks, type B supplied-air respirators, which are intended for nonemergency use, are similar to the type A described above except that they have no blowers, and some of the parts are lighter. These hose masks are approved with 25 to 75 ft. of hose, which terminates in a funnel fitted with a 100-mesh screen. This device should not be used in atmospheres immediately dangerous to life.

Air-Line Respirators. Air-line, or type C, supplied-air respirators usually consist of a compressed-air supply system; a hose of relatively small internal diameter; a detachable coupling; an air-flow control valve, or orifice, that cannot be adjusted to an air flow of less than a specified minimum; and either a full or half-mask facepiece, helmet, or hood. The compressed air should be delivered through a trap and filter, if necessary, to make certain that it is not contaminated with rust, oil mist, or water. If the air is supplied by a piston-type compressor, some safeguard should be used to prevent its accidentally overheating and oxidizing the lubricant with the formation of carbon monoxide. A thermal cutout located at the exhaust port has been proposed for this purpose. This respirator gives protection from all contaminants, but its safe usage is limited to situations that are not immediately dangerous to life, from which the wearer can escape without the use of a mask. When a half-mask facepiece is used, leakage around it is possible; also, there is no provision for breathing respirable air in the event of failure of the air supply.

Loose-fitting helmets or hoods, to be effective, require a flow of respirable air of at least 6 cu. ft. per minute. It is a serious mistake to provide valves by which the wearer can adjust his air supply to less than this minimum safe amount. The air supply should be engineered to deliver into the helmet or hood the correct amount of air as measured by a suitable air-flow metering device. The flow should then be checked periodically to see that the air flow does not fall below this minimum.

Abrasive-Blasting Respirators. Abrasive-blasting respirators are either type A or type C supplied-air respirators modified by the addition of a suitable covering to protect the head and shoulders of the wearer against impact and abrasion by rebounding abrasive material.

2. Self-Contained Air- or Oxygen-Supplying Equipment

The most common respiratory protective devices for supplying oxygen are self-contained oxygen-breathing apparatus, available in $^1/_2$-, 1-, and 2-hour sizes. This apparatus consists of a cylinder of compressed oxygen, a reducing valve, an admission valve, a breathing bag, breathing tubes and mouthpiece with valves to control the direction of flow of inspired and expired air, a regenerator box containing an absorbent for removing carbon dioxide, and a cooling chamber. The entire device, which operates on a closed-circuit principle independent of the environmental atmosphere, is worn by the user. When the apparatus is adjusted, and the cylinder valve opened, oxygen flows in turn through reducing and admission valves into the breathing bag until its expansion releases a spring that closes the admission valve. As oxygen is breathed from the bag, the exhaled air is passed through the absorbent in the regenerator, then through the cooler, and back into the bag. Whenever the bag tends to collapse, its weight opens the admission valve, replenishing the oxygen supply in the bag.

The self-contained oxygen-breathing apparatus is approved for use only with mouthpiece and nose clips, and therefore requires gastight goggles when used in irritant gases. Even though this is not approved practice, it has been frequently and safely used with a modified gas-mask facepiece in certain situations. This apparatus protects the wearer against atmospheres deficient in oxygen, as well as from contaminants immediately dangerous to life. However, in the use of this device as well as the hose mask, the wearer is limited by what the skin will endure either from the standpoint of irritation or absorption—for instance, in atmospheres containing hydrogen cyanide. The oxygen-breathing apparatus is the heaviest respiratory protective device, and is a rather complicated mechanical apparatus. It requires training and experience in its use and maintenance, and it is important that the wearer have a clear understanding of its mechanical parts before attempting to wear it into an immediately dangerous atmosphere. Since all state codes, and the ASA code covering approved respiratory protective devices, are based upon the results of the approval tests of the United States Bureau of Mines, it is logical to be guided by the current list of approved devices from the Bureau.[2]

3. Newly Developed Air- or Oxygen-Supplying Devices

New and somewhat simplified self-contained air- or oxygen-supplying devices utilizing compressed air or oxygen, as well as self-contained oxygen-breathing apparatus having potassium peroxide regeneration cartridges to supply oxygen and remove carbon dioxide, have found useful application. Each cylinder or canister for these devices is approved for either 30 or 45 minutes use. These devices are simplified and more adaptable to certain industrial uses than are the conventional type. However, they require training and experience for their safe use and should never be considered as either foolproof or as simple as a gas mask.

C. UNAPPROVED EQUIPMENT

There are many unapproved devices offered for sale to be used in many situations, but before selecting one of these devices it is well to consider the responsibility involved. If a respiratory protective device is proposed as a means of preserving health, or of saving a life in the event of an emergency, it is not something one can take chances with in order to save a few cents or to oblige a favorite salesman. If the atmospheric contaminant is harmful, or suspected of being harmful, and United States Bureau of Mines approved respiratory protective devices are provided, there is evidence of an attempt to protect the health of the persons involved; but if unapproved devices are provided, negligence might be inferred. Few employers are in a position to establish the efficiency of respiratory protective equipment by dependable experimentation, and in the main they are therefore dependent upon outside advice. To use unapproved equipment in industrial situations is to assume the role of guinea pig to find possible shortcomings.

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[2] *List of Respiratory Protective Devices Approved by the Bureau of Mines*, obtainable currently from the U. S. Bureau of Mines, 4800 Forbes St., Pittsburgh 13, Penna.

1. *Filtering Efficiency against Paint Mist*

The percentage collecting efficiency of a respirator is perhaps not of as much interest as is the amount of contaminant passing through the filter under various circumstances, because the amount passing through the filter determines the extent of a workman's exposure. It is only fair to state that practically any mechanical filter arrangement will remove some particulate matter from the air passing through it. Where the exposure is a borderline one, that is, near or only slightly above accepted "safe" practice, a device of low efficiency may lower the exposure to within accepted limits. This is, of course, not true of gases or solvent vapors, as these are not affected by mechanical filters. Table 2 indicates the filtering efficiency of some unapproved respirators in restraining lead in paint-spray mist.[3] The tests upon which the table is based were conducted for approximately one-half hour at an air flow of 32 liters per minute.

TABLE 2

Filtering Efficiency of Respirators in Paint Mist

Filter material	Resistance (inches of water) to air flow at 85 liters/min.		Lead (mg./cu. m. in air)		Filtering efficiency (per cent)
	Before test	After test	Before filter	After filter	
Sponge	0.3	0.3	395	63	84.0
Paper *a*, 1 ply	1.0	1.6	397	10.7	97.3
Paper *b*, 1 ply	0.2	0.6	374	15.0	96.0
Paper *b*, 2 plies	0.5	0.9	353	6.0	98.3
Gauzy tissue paper, 4 plies	0.5	0.8	498	39.8	92.0
Cotton flannel, 2 plies	0.2	0.4	458	22.9	95.0
1-ply silk, 3-ply cheesecloth	0.05	—	450	117.0	74.0
Cotton wool between cheesecloth	0.2	0.2	351	21.1	94.0
Charcoal cartridge with 20 plies of gauzy tissue paper	3.5	4.4	524	1.6	99.7

Although each of these materials has an efficiency of 74 per cent or better, none approaches the requirement of delivering air having less than 0.15 mg. lead per cubic meter of air. These tests indicate that even a layer of absorbent cotton between cheesecloth may remove 90 per cent or more of the lead pigment in paint mist. For an isolated short exposure with no other protection available, this would be worth while. However, when a workman is exposed to a mist containing, say, 350 mg. lead per cubic meter, his exposure through the respirator would still be over 100 times that of accepted safe practice. Obviously, percentage efficiency is not an acceptable means of rating respirators. The significant factor is the amount of leakage through the filter and such is now used in respirator testing for United States Bureau of Mines approval. In general, filters are less efficient against silica sprays and silica dusts than against lead, and the protection afforded against silica by many unapproved respirators is not of a high order.

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[3] S. H. Katz, E. G. Meiter, F. H. Gibson, *U. S. Pub. Health Service Bull.* No. **177**, 1928.

2. Unreliable Carbon Dioxide Absorbents

Although the soda lime presently used in respirators to neutralize acid gases is not adversely affected by organic vapors, some alkaline absorbents used in the past as fills for gas-mask canisters and for cartridges used in absorbing carbon dioxide in oxygen-rebreathing apparatus are known to have become paralyzed or poisoned by the vapors of ethyl alcohol. This was verified by experimental work in which carbon dioxide, passed through the granular absorbent, was absorbed completely until ethyl alcohol vapor was also introduced, whereupon the carbon dioxide passed through unchecked. After the ethyl alcohol was removed by aeration, the alkaline absorbent again reacted with carbon dioxide in a normal manner. The use of this and similar alkaline absorbents may have resulted in adverse experience with some of the earlier types of oxygen-rebreathing apparatus, when worn by members of mine rescue teams after they had partaken of alcoholic beverages.

III. Selection of a Respirator

In the selection of a respirator careful consideration should be given the chemical, physical, and toxicological properties of the contaminating material; possible secondary or by-products that may occur; whether the exposure is immediately dangerous, or whether injuries might arise only after prolonged exposure; the nature and amount of work to be done by persons wearing devices; whether the exposure will be brief or prolonged; whether sufficient consideration has been given to other possible control measures. The person making the selection should know the principles, design, scope, use, limitations, advantages, and disadvantages of the respiratory protective equipment available (see also Figure 2).

Desirable qualifications of a respirator are: low resistance to inhalation and exhalation, smallest possible dead-air space, long service life, least interference with movement and vision, light construction, ruggedness, dependability, and low cost. The two factors that most influence fatigue are the resistance to inhalation and exhalation and the size of the dead-air space. Resistance to breathing is tiresome to muscles that are not trained to the effort; especially is this true of exhalation, which is normally passive. Excessive resistance can cause serious irregularities in respiration in untrained persons. The dead-air space—space between the facepiece and the wearer's face—serves to enlarge the approximately 150 ml. normal space intervening between respiratory tissue of the lungs and the environmental atmosphere. The air in this space is partly depleted of oxygen and rich in carbon dioxide, and when the volume of the space is unnecessarily large disturbances of respiration may result.

TABLE 3

Typical Situations and Suitable Respiratory Equipment

	Respirator						
Environment necessitating protection	Dust, mist, or fume	Chemical cartridge	Gas mask	Air-line	Hose mask	Abrasive-blasting	Oxygen-breathing apparatus
Abrasive blasting							
Dust, inside cabinet	–	–	–	–	–	++	–
Dust from leaks, outside cabinet	++	–	–	–	–	–	–
Asbestos workers	++	–	–	±	–	–	–
Dusts from grinding, buffing, polishing, sweeping, screening, shoveling, mining, tunneling, and stone cutting	++	–	–	+	–	–	–
Fires in chemical plants or involving high concentrations of toxic gases	–	–	+	–	±	–	++
Fires in dwellings, offices, or factories	–	–	++	–	±	–	+
Fumigation	–	–	++	–	++	–	+
Metal fumes from soldering, brazing, welding, flame cutting	++	–	–	++	–	–	–
Metalizing	+	–	–	++	–	+	–
Mine fires and explosions	–	–	+	–	–	–	++
Paint spraying	+	+	–	++	–	–	–
Oil-storage tanks (crude)	–	–	–	–	++	–	±
Refrigeration plant							
Leaks in ammonia lines (large)	–	–	–	–	++	–	+
Leaks in ammonia lines (small)	–	–	++	–	+	–	–
Sewers, wells, silos, unventilated holds of ships	–	–	–	–	++	–	+
Sour crude oil in ventilated areas	–	–	++	–	+	–	–
Toxic gases							
Less than 2 per cent	–	–	++	–	++	–	–
More than 2 per cent	–	–	–	–	++	–	+
Vats for beer, wine, vinegar, etc.	–	–	–	–	++	–	+

– Not suitable. + Some application. ++ Usually preferred.

It is essential that the provision of respirators be under competent supervision; and not only must the correct respirator be provided, but also it must be clean, sterilized, and maintained in good condition and the wearer must be properly instructed in its purpose, use, and care.

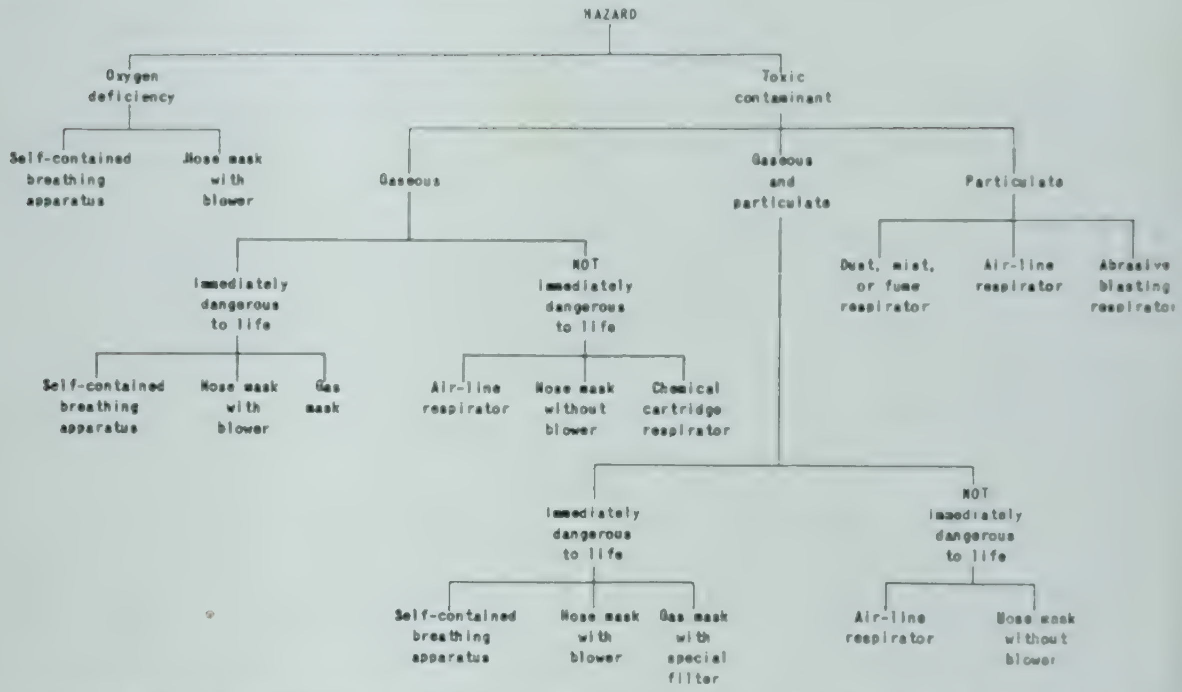
HAZARD
Oxygen deficiency
Toxic contaminant
Self-contained breathing apparatus
Hose mask with blower
Gaseous
Gaseous and particulate
Particulate
Immediately dangerous to life
NOT immediately dangerous to life
Dust, mist, or fume respirator
Air-line respirator
Abrasive blasting respirato
Self-contained breathing apparatus
Hose mask with blower
Gas mask
Air-line respirator
Hose mask without blower
Chemical cartridge respirator
Immediately dangerous to life
NOT immediately dangerous to life
Self-contained breathing apparatus
Hose mask with blower
Gas mask with special filter
Air-line respirator
Hose mask without blower

Figure 2. Outline for selection of respiratory protective devices. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

IV. Cleaning and Sterilizing

When respirators have been worn several hours, they should be scrubbed with warm water and soap, and if they are to be given to another person they should first be sterilized. Several disinfecting solutions including 70 per cent alcohol have been used. Care must be exercised that the agent chosen does not damage any part of the device, and that, if it is an irritant or sensitizer, the last traces be washed off before the respirator is returned to use. Where doubt exists, the manufacturer of the device should be consulted regarding possible adverse effects of a proposed sterilizing agent on his product.

V. Examining a Respirator

First determine whether the device has been approved for the purpose planned. See whether the rubber parts are pliable and in good condition. Examine the valves and test for tightness as described below for facepiece and breathing tubes. Check the breathing resistance by machine (manometer reading at measured air flow) or by putting the mask on. If the device is to be worn in an immediately dangerous atmosphere, check the facepiece and breathing tubes for tightness by putting the mask on, closing off the air inlet, inhaling and holding the breath for about ten seconds, during which time the facepiece should remain collapsed.

Filters or canisters should be examined and replaced where necessary. In making a decision as to the need for replacement two facts are of most help: first, the amount of resistance offered to breathing through the device when it is put on in normal air; second, the record of date of purchase and time of actual usage in contaminated air, which should always accompany each canister. Mechanical filters that do not offer excessive resistance to air flow and are obviously intact may be considered to retain their original efficiency—in some cases to have improved it—and therefore do not need replacing. Canisters may need replacing if the resistance has become too great from any cause, such as corrosion, caking of chemicals, etc. Canisters may likewise need replacing if the efficiency of the material within them has been depleted, as by chemical exhaustion due to old age or too much usage. If uncertainty exists, yet it is desired to use the canisters, they may be tested by inhaling through them some relatively harmless gas having chemical properties and reactions similar to the gas or vapor in which the device is to be used. An odorous or irritant, relatively innocuous, material of the class against which the device is designed to protect may be used to make a test atmosphere and the device tried out in it before being used in dangerous situations. As pointed out previously, canisters for protection against carbon monoxide are not reliable after about two hours actual use and should not be used for this purpose, even though their appearance may be good.

CHAPTER XII

The Pulmonary Dust Diseases*

O. A. SANDER, M.D.†

I. Introduction

The industrial hygienist and the industrial physician are concerned with dust because of its almost constant dispersion in air, where it may be inhaled and in some instances cause disease. This suspension of finely divided particles in the air may not ordinarily attract attention in rural areas but the smokiness of large cities is immediately apparent. Clean country air may contain as much as 0.2 mg. dust per cubic meter of air, whereas the average amount in city air during the winter months is approximately 0.5 mg. per cubic meter of air.[1] Thus, the cloud of dust that arises from a stonecutter's chisel is an excessive amount superimposed on that which is present in the already dust-laden air.

In addition to the medical problems, the legal entanglements which may revolve around dustiness are often of sufficient complexity that months of careful study are required to determine or fix responsibilities. In cities where general industrial smoke contamination is a perennial problem, individual firms may be selected each year to bear the brunt of civic ire, and each year certain luckless corporations are forced to defend themselves in civil suits that are based almost entirely upon claims having no factual evidence for support. Medical-legal situations may be even more complex than the nonmedical problems and are complicated by numerous intangible factors. Not only does the exact nature of the disease and its relation to dust require proof, but the actual source of exposure must be determined so that a nondusty industry will not be held responsible for dust disease that may have resulted from exposure many years prior to the onset of the disease.

This chapter is written as an attempt to bring together facts necessary for a general understanding of dust and dust diseases. The presentation in the first portion is somewhat general so that the contents can be readily grasped by physicians without an extensive background in engineering or physics, and by engineers and industrial hygienists without medical training. In the later sections an attempt is made to review the pneumoconioses in sufficient detail to aid the physician called upon to examine employees whose work exposes them to dust.

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* Revision of Chapter 15, "Dust and Its Role in the Causation of Occupational Disease," by Edward E. Dart, M.D., in first edition.

† Section on lung physiology and function written by R. P. Jahn, M.D., Milwaukee, Wis.

[1] J. M. DallaValle, *Micromeritics: The Technology of Fine Particles*. Pitman, New York, 1943.

A. PROPERTIES OF DUST

The important physical and chemical properties of dust have been summarized by Drinker and Hatch,[2] and much of the material presented here was obtained from that source.

1. Settling rates. Suspended microscopic dust particles, like any other free body, are attracted to the earth by gravity. However, because of their small mass and the relatively great resistance of the air, they do not fall according to the usual laws of gravity. Settling rates are much greater for large than for small particles. A settled dust, accordingly, may contain a proportionately greater percentage of large particles than the contaminated air from which it settled and in which the fines predominate. Ore as it is found in mines may contain a certain amount of quartz, which is frequently harder than the other minerals present. Because of this relative hardness the quartz may be ground less finely in drilling operations. Much of this coarser quartz dust may settle out from the air in the working area with comparative rapidity, leaving a smaller percentage of quartz in the atmospheric dust than may be present either in the parent material or in the settled rafter dust.

2. Flocculation. Dust produced by crushing or grinding a material such as quartz differs from fume such as magnesium oxide in respect to its tendency to flocculate. Freshly formed fume particles are usually well below 0.3 μ and accordingly exhibit marked Brownian movement. Because of this and perhaps other factors, they tend to collide and form flocs which, because of their larger size, settle out relatively quickly. Such masses tend to adhere to vertical walls and projecting surfaces.

True dust is much less apt to flocculate than is fume, and any flocs formed are much more loosely bound together. Settling of dust clouds is therefore much less pronounced than is settling of fume clouds. As a dust cloud clears, the size of the particles remaining in suspension decreases and the degree of dispersion increases, that is, the ratio of flocculated to discrete particles becomes less. In a metallic fume, on the other hand, both the percentage of flocs and their size increase with the age of the cloud.

Turbulence in the air increases floc formation in fume clouds by increasing the collision frequency, but it does not improve the settling rate of dust.

Humidity below saturation is said to have little effect on flocculation time. However, humidity to the point of supersaturation is an important factor, as the dust particles function as nuclei on which water may condense, thus increasing particulate size.

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[2] P. Drinker and T. F. Hatch, *Industrial Dust,* 2nd ed., McGraw-Hill, New York, 1954.

3. Wetting. Wetting is primarily an adsorption phenomenon in which the surfaces of the particles become covered with a film of water. Most liquids tend to spread on plane surfaces, but great force must often be used to wet dust, probably because the particles are already surrounded by a film of air. Wetting is of importance in dust sampling and in control of dust.

Three factors have been described by Drinker and Hatch as of importance in the wetting of dust. First, it is necessary to maintain intimate and vigorous contact of long duration between the dust and liquid. Second, it is advantageous to apply the liquid immediately at the dust source, because the heat usually generated in producing dust by drilling or grinding hampers air adsorption and because continuous flooding at the source excludes air. Third, wetting agents may be used to increase the wetting power of water.

4. Electrical properties. Dust particles are electrically charged and accordingly are attracted to oppositely charged particles. If, therefore, particles in a dust suspension are given an electrical charge, the tendency for floc formation should be increased. Attempts have been made to utilize electrically induced flocculation as a method of air purification but without great success. Electrostatic precipitation, on the other hand, has been used quite successfully for collection of dust and fume, but such precipitation depends upon the attraction of the electrically charged particles to an oppositely charged plate rather than upon flocculation.

5. Optical properties. Dust or moisture particles reflect light and it is this light, reflected from dust particles otherwise too small to be seen, that makes them visible when a beam of light enters a darkened room. The scattering of a beam of light by dust or mist is known as the Tyndall phenomenon. The optical properties of suspended particles in air vary with their shape, their transparency, and especially their size. With particles larger than the wave length of light (about 0.7 μ), the strength of the Tyndall beam varies directly with particle surface area and concentration; thus, for a given weight concentration it varies inversely with the particle size. Attempts have been made to utilize these optical properties in the measurement of dust concentration, but variation in the size of the particles makes such determinations unreliable.

B. ATMOSPHERIC DUST CONCENTRATIONS AND PARTICLE SIZE

Whenever a solid or liquid is ground or broken into particles as small as dust, the surface area is greatly increased. Thus, if a cube of mineral 1 cm. in each of its dimensions is ground into small cubes 1 cu. μ in size, there will be 10^{12} particles with a total surface area of 6 sq. meters as compared with 6 sq. cm. for the original cube. This great increase in surface area is largely responsible for the increased chemical activity of finely ground materials and may be an important factor in the production of silicosis.

Industrial dust concentrations may range from the amounts present in "pure air," in operations where no dust is produced or where there is adequate dust control, to as high as 2 billion particles per cubic foot of air, in rock drilling. Dalla-

Valle[1] has pointed out that more than 50 per cent of industrial dusts are greater than 1 μ in size while in atmospheric dust the median size is approximately 0.5 μ. Bloomfield[3] found that only 20 per cent of the particles found in air in fifty industries were smaller than 1 μ and that the median size was 1.3 μ; he suggested that most of the particles of smaller size found in industrial atmospheres were those normally present in air. In certain industries, however, such as pneumatic rock drilling, large numbers of particles well below 1 μ in size are produced.[4]

II. Classification of Dust Based on Its Effect in the Body

The industrial hygienist is interested in dust because of its effect on the human body. Therefore, a limited classification of dust from this viewpoint may form a basis for relating the chemical composition of dust to the anatomical and physiological reactions that occur.

Pneumoconiosis is defined as: *Any dust particles retained in the lymphatic depots of the lungs.* The term generically carries no implication of fibrosis or other reaction and no implication of disturbed function of the lungs. Nor is it specific with relation to the type of dust.

If we accept this generic definition of "Pneumonokoniosis," which Zenker coined in 1866 (the term was shortened by the International Labor Office in 1932), then all humans have some degree of pneumoconiosis. In city dwellers it is the anthracotic pigmentation from air pollution and in farmers the dust from the field and from the grains. The only reason such deposits are not generally thought of as pneumoconioses is that they usually are not visualized by x-ray. Even where the soil is fairly high in free silica, insufficient silicotic nodulation results to be seen by x-ray. Also, most dusts in the general atmosphere have a low grade of radiopacity, so that such deposits in the lungs do not cast direct shadows. Therefore, our chest roentgenograms are read as showing "healthy lungs," even though we know that we all have some degree of retained dust or pneumoconiosis.

There are those who, for medical-legal reasons, would limit the meaning of "pneumoconiosis" to the fibroses resulting from industrial dust exposure. They argue that ordinary dust retention should not be dignified with such a word. In addition, a number of state compensation laws list "pneumoconiosis" as a compensable occupational disease. However, there are others who feel that such a strict limitation of meaning of the term is artificial and that it disregards the occupational dust deposits which are benign and do not cause fibrosis (the so-called "benign pneumoconioses"). To the authors it seems more sound scientifically to think in terms of the generic definition and to consider that all humans have pneumoconiosis. When a doctor says that so-and-so has pneumoconiosis, the reply ought to be: "We all have. Please specify. Is it occupational? What type of dust?" Certainly the word has no place in occupational disease laws where the compensable diseases should be carefully and specifically defined.

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[3] J. J. Bloomfield, *U. S. Pub. Health Repts.*, **48**, 961 (1933).

[4] T. Hatch and C. L. Pool, *J. Ind. Hyg.*, **16**, 177 (1934).

A useful classification of the pneumoconioses, based on the effect of dust in the lungs, is as follows:

A. Inert Dusts ("benign pneumoconioses"). Little or no fibrous tissue reaction; dormant deposits in pulmonary lymphatics and root lymph nodes, which are visualized by x-ray when the material is radiopaque. They do not appear to have a predisposing effect on tuberculosis or other infection and do not cause impaired lung function.

1. Carbon (smoke, soot): Most anthracosis due to coal deposits also benign, but excessive deposition over many years may lead to disabling emphysema (see below).

2. Calcium (cement, marble, gypsum): Generally not visualized by x-ray. Cases called "calcicosis" in past probably were endogenous calcification due to fungous diseases such as histoplasmosis.

3. Iron (confined welding, grinding, steel cutting, and burning): Radiopaque deposits visualized by x-ray as discrete nodulation. "Siderosis" is a perfectly proper term for such iron pigmentation, but there should be no implication of fibrosis in the term.

4. Artificial abrasives (carborundum, emery, aluminum oxide): Have replaced sandstone in grinding wheels.

5. Aluminum (or hydrated aluminum): Used in some areas in prevention and treatment of silicosis.

6. Barium and tin (radiopaque deposits): Baritosis and stannosis.

B. Proliferative Dusts ("fibrotic pneumoconioses").

1. Silica (crystalline free silica, SiO_2, as quartz, flint, etc.): Typical fibrous nodules spread throughout both lungs and visualized by x-ray. Usually normal alveolar walls. Simple silicosis. (*a*) Most silicosis today modified by other components in dust, such as Ca, Al, Fe, and C. (*b*) No disability unless conglomerate or complicated with tuberculosis or advanced emphysema. (*c*) Relationship of silicosis and tuberculosis: Primarily reactivation and spread of pre-existing tuberculous foci. Combined lesions frequently result in chronic massive progressive fibrosis. (*d*) Relationship with heart disease: Right heart strain (cor pulmonale) only with advanced stages of silicosis, silicotuberculosis, and emphysema.

2. Asbestos (hydrated magnesium silicate): Mechanical plugging of bronchioles by long fibers and peribronchiolar fibrosis. Fibrosis may result from breakdown of asbestos bodies. Asbestosis.

3. Other silicates? (talc, kaolin, soapstone, mica, feldspar): Reported fibrosis with some silicates may be due to quartz impurities.

4. Bauxite processing (Shaver's disease): Diffuse fibrosis with marked emphysema and frequent spontaneous pneumothorax. Due to silica fume modified by aluminum fume?

5. Diatomaceous earth: Amorphous and only slightly reactive before calcining; then crystobalite formed, causing diffuse fibrosis.

6. Coal dust (coal workers' pneumoconiosis): Focal emphysema and minimal

fibrosis, usually not disabling, but there may be marked disability when emphysema is advanced and fibrosis is massive and progressive.

7. Beryllium (beryllium oxide): Generalized granulomatosis. Marked disability when largely pulmonary because of interalveolar edema and fibrosis. Probably a sensitivity response and not a true pneumoconiosis. Berylliosis.

Other dusts, which are not of interest here because of not being retained in the lungs, are those that may cause chemical irritation of the upper respiratory mucous membrane, such as acids, alkalies, fluorides, chromates, cadmium, nickel carbonyl, and so forth. Many dusts inhaled into the lungs (lead, manganese, and so forth) are completely absorbed by the blood and may cause systemic poisoning. Many dusts, principally those that are organic, are purely allergens and may cause asthma and hay fever. Others, such as zinc oxide and cotton, may cause transitory chills and fever.

III. Anatomical Factors of Importance in Injury by Dust

The fate of inhaled dust in the body can be understood only by knowing something of the anatomical structures and physiological reactions involved in respiration.

The air passageway consists of the nose, pharynx, trachea, bronchi, bronchioles, and alveoli. The relationship of these various structures is shown in Figure 1.[5]

1. Nose. The portions of the nasal cavities just within the external nares are lined with skin containing hairs. The remaining parts of the nasal cavities are lined with mucous membrane, composed on its surface of ciliated and mucus-secreting cells. This tissue is highly vascular and contains freely anastomosing venous channels. The nasal passages are connected directly with the air sinuses in the skull.

The hairs in the entrance of the nose and the mucous material secreted by the lining membrane collect many of the larger inhaled particles. The cilia of the entire respiratory tract tend to move material toward the mouth, those of the nose tending to force the mucous and particles in it toward the pharynx. The importance of the nose as a protective mechanism has been indicated by G. Lehmann.[6] This investigator studied 426 miners, of whom 241 had silicosis and 181 were normal, and found the median efficiency of nasal filtering in the silicotics to be 27.5 per cent and in the normals 45 per cent. He concluded from this that persons who develop silicosis do so, in part at least, because of a faulty filtering mechanism in the nose.

2. Pharynx. The pharynx is a common pathway for food and air, connecting the nasal passage with the oral pathway and with the trachea. Its nasal portion is lined with ciliated epithelium.

3. Larynx and trachea. The larynx lies between the pharynx and trachea. It

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[5] L. E. Hamlin, *Rocky Mt. Med. J.*, **41**, 391 (June, 1944).

[6] G. Lehmann, *Arbeitsphysiol.*, **7**, 147 (1933); see also *J. Ind. Hyg.*, **17**, 37 (1935).

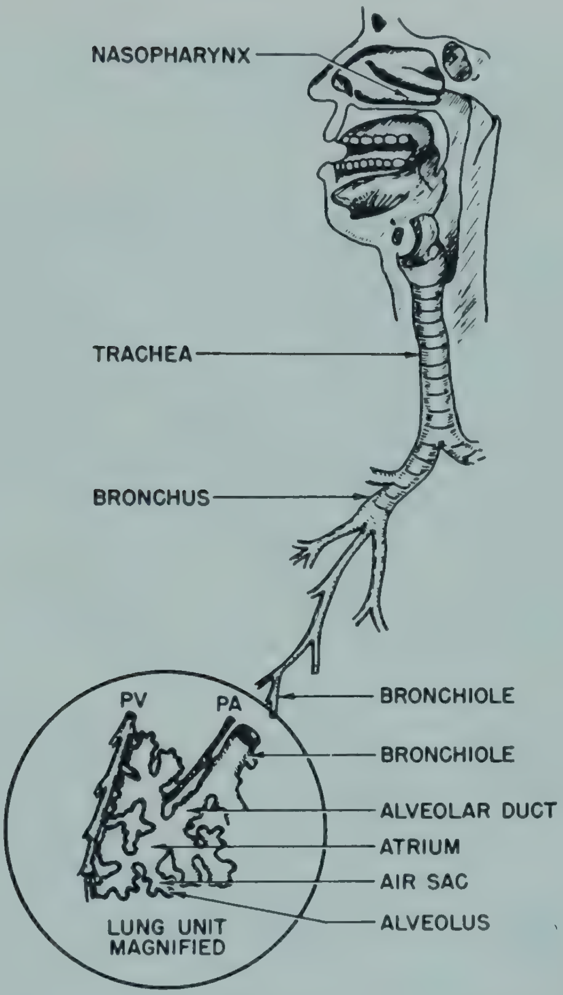

Figure 1. Diagrammatic representation of the respiratory tract.

is strengthened by strong cartilages, contains the vocal mechanism, and has at the opening to the oral passage a valvelike structure—the epiglottis—which closes the tracheal opening during swallowing to prevent food from entering the respiratory pathway. The trachea is a tube 1 to 2 cm. in diameter, strengthened by cartilage rings and, like the nasal pharynx, lined with ciliated and mucus-producing cells. The relationship of the trachea and bronchi to the lungs as a whole is shown in Figure 2.[7]

4. Bronchioles and alveoli. Macklin[8] divides the bronchial tree into two parts that may be compared to the trunk and branches of a tree. The first part, which extends from the trachea to the *terminal bronchioles* inclusive, serves simply as an air conduit, and, like the branches and twigs of a tree, has no respiratory function.

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[7] J. Sabotta and J. P. McMurrich, *Atlas of Human Anatomy,* Vol. II. Stechert, New York, 1933.

[8] C. C. Macklin, *Am. Rev. Tuberc.,* **25,** 363 (1932).

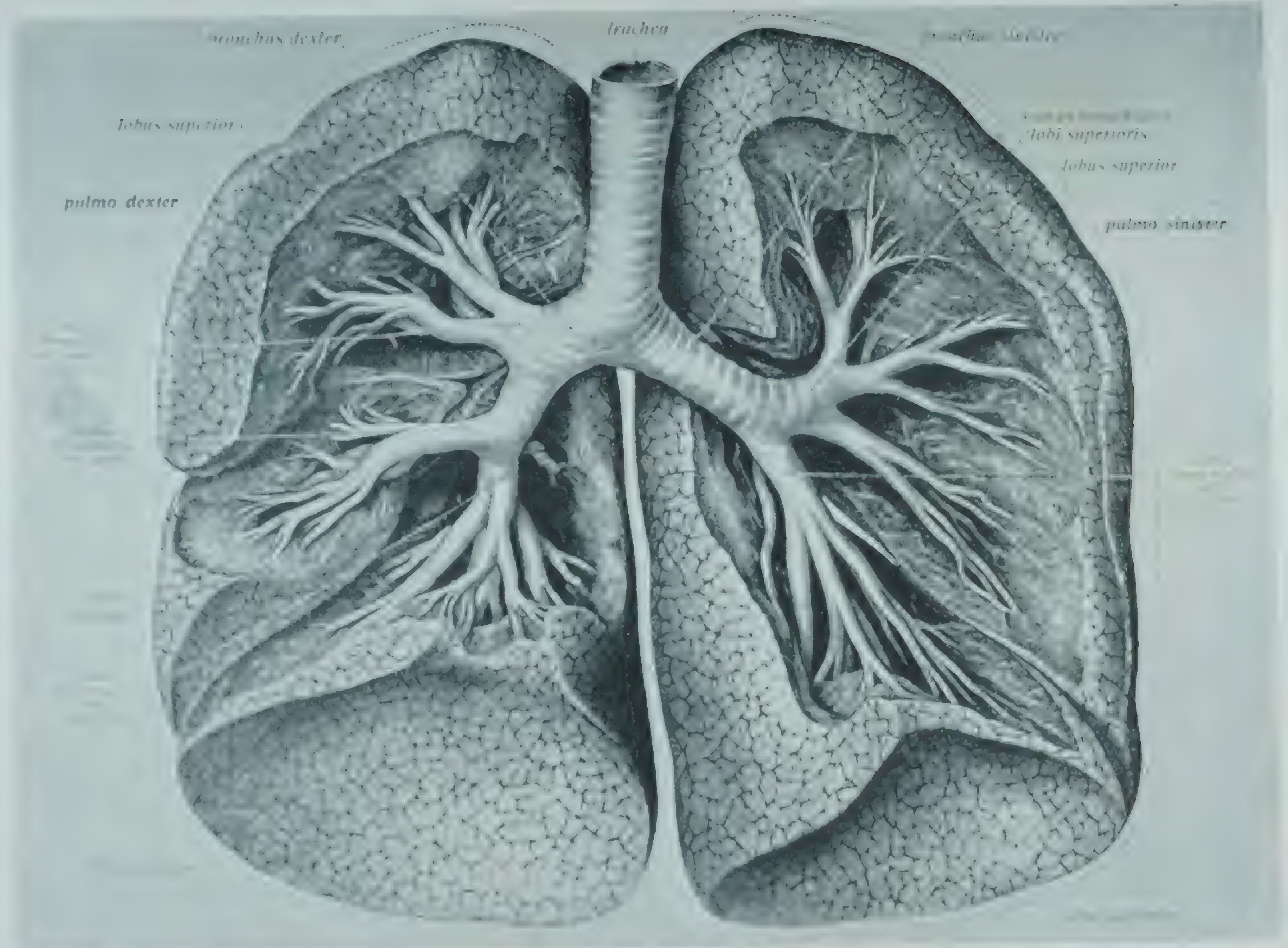

Figure 2 The two lungs with the trachea and the branching bronchi exposed by removal of portions of the lung substance.[7]

The terminal bronchioles are the last of a series of subdivisions of these nonrespiratory bronchioles. The muscular tissue in their walls is more highly developed than that in any other part of the bronchial tree and when fully contracted exerts a sphincterlike action which can completely shut off the air supply to the chambers beyond.

The structures lying distal to the terminal bronchioles are the "leaves" of the bronchial tree. They have a respiratory function: the interchange of gases between air and blood occurs through their walls. The respiratory portion consists of the respiratory bronchioles, alveolar ducts, alveolar sacs, and pulmonary alveoli. The cluster formed by a related group of these structures constitutes a *lung unit* or *primary lobule*. This is the distensible or bellows part of the lung.

The *respiratory bronchiole* as described by Best and Taylor[9] has the same diameter as the terminal bronchiole, of which it appears as a branch or a continuation. Fve or six *alveolar ducts* arise from each respiratory bronchiole. After a variable number of rebranchings each alveolar duct gives rise to from three to six dilatations, the *alveolar sacs*. The bays in the walls of these sacs constitute the *pulmonary alveoli,* which are lined by a single layer of flattened epithelial cells cemented together. The alveolar walls contain elastic fibers and a rich network of capillaries. Frequently only a single capillary channel intervenes between the walls of adjacent alveoli. The blood in the capillaries is therefore separated from the air in the alveoli by only two membranes of the utmost delicacy—the alveolar and capillary walls, so the greatest freedom is afforded for the diffusion of gases from the blood to the alveolar air and from the alveolar air to the blood.

The bronchioles, as they approach the periphery of the lung, branch and rebranch repeatedly, diminishing in length with each subdivision. The first branchings are about 1.5 mm. in length and from 0.3 to 0.4 mm. in diameter. The terminal and respiratory bronchioles are from 0.2 to 0.5 mm. in length but of about the same diameter as the more central subdivisions. That is, the bronchioles, though progressively shorter, show practically no decrease in diameter as they pass toward the periphery. The alveolar sac, however, is considerably wider than either the respiratory bronchiole or the alveolar duct from which it arises. The pulmonary alveoli are semiglobular and have diameters ranging from 0.075 to 0.125 mm.; the total number in the lungs has been estimated by Zuntz at 750 million. Willson[10] estimates the total epithelial surface of the lungs at 70 sq. meters; of this, probably 55 sq. meters, over 25 times the surface area of the skin, is respiratory.

From these facts it is apparent that lung tissue offers by far the best medium of any in the body for the absorption of materials that may come in contact with it.

5. Blood vessels and lymphatics. Except in the alveolar areas the blood vessels and lymphatics follow rather closely the path of the bronchial tree. The relationship in the periphery of the lung is shown clearly in Figure 3.[11]

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[9] C. H. Best and N. B. Taylor, *The Physiological Basis of Medical Practice*. 3rd ed., Williams & Wilkins, Baltimore, 1943.

[10] H. G. Willson, *Am. J. Anat.,* **30,** 267 (1922).

[11] W. S. Miller, as reproduced by Pendergrass in A. J. Lanza, ed., *Silicosis and Asbestosis*. Oxford Univ. Press, New York, 1938.

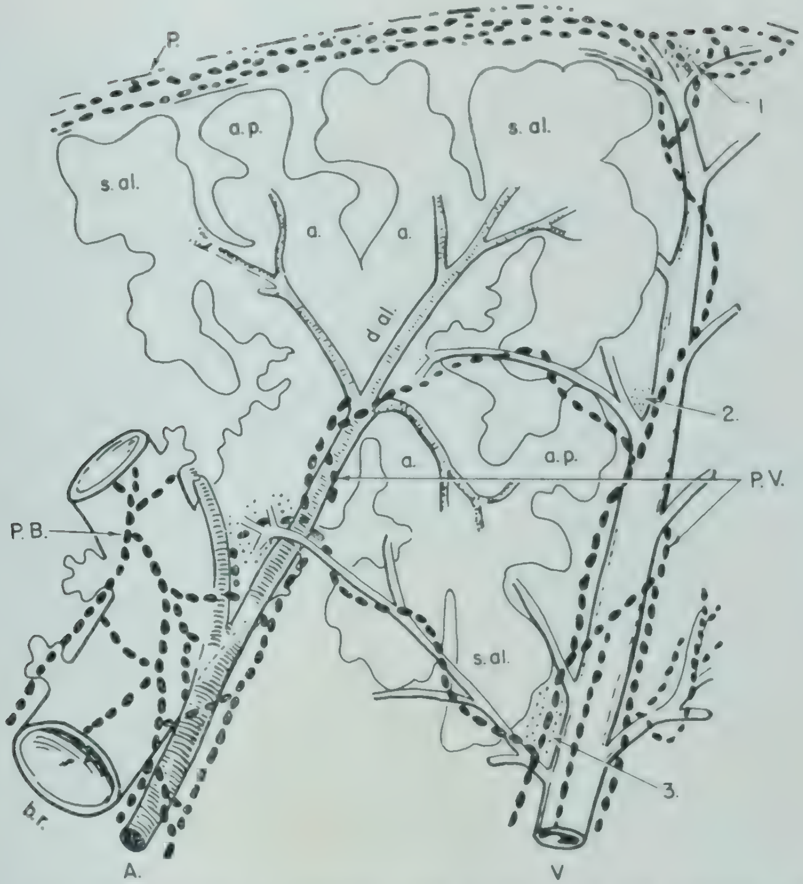

Figure 3. Composite diagram (modified from Miller[11]) of the primary lobule lymphatic system, indicating the primary distributions or accumulation points for dust that will lead to predominant phases of pneumoconiosis: *b.r.*, respiratory bronchiole; *d.al.*, alveolar duct; *a.*, atria; *s.al.*, sacculi alveolare; *a.p.*, alveoli opening into respiratory bronchioles and alveolar ducts in close relation with the origins of peribronchial and perivascular lymphatics; *A.*, branch of pulmonary artery, accompanying the air passages; *V.*, branch of pulmonary vein in interlobular septum; *P.*, pleura; *P.B.*, peribronchial lymphatics; *P.V.*, perivascular lymphatics; *1.*, *2.*, *3.*, and other dotted areas, lymphoid deposits. (By previous permission of Dr. W. S. Miller.)

The lymphatic system consists of vessels that carry fluid similar to the blood plasma and nodules composed largely of protective and phagocytic cells. The lymphatic vessels and lymphoid tissue are important in connection with a study of dust because most of the dust particles finally lodge in the peribronchial and interstitial lymphoid tissues, carried there by wandering phagocytic cells.

6. Phagocytes. In the alveolar spaces there are large cells capable of ingesting foreign material and having the power of independent motion. A large number of these ameboid forms appear wherever foreign material enters the lungs. After ingesting the exogenous particles, some of these cells pass into the blood stream and finally lodge in the spleen and liver or move elsewhere in the lung tissues; the majority, however, make their way to the lymph vessels and eventually to accumulations of lymph tissue, where they lodge. This resting place may be anywhere in the lung. Some phagocytes migrate peripherally to the pleura and others centrally to the hilus. In the lymph tissue the foreign material may be absorbed, may remain in an inert state, or may, by some chemical reaction, initiate pathological changes such as the formation of silicotic nodules.

IV. Physiological Factors of Importance in Injury by Dust

1. Volume of air inhaled. Just as we are interested in the amounts of dust suspended in air, so are we also interested in the amount of air inhaled by men under different conditions. This has been discussed in Chapter VI.

2. Dust retention. Before we can arrive at a logical basis for determining maximum permissible concentrations, it is necessary to know what proportion of inhaled dust is retained. Since most dust-collecting apparatus imposes considerable resistance to the passage of air from the lungs, satisfactory results were not obtained in such studies until Baumberger[12] used an electrostatic precipitator with tubes large enough to reduce the resistance to a negligible factor. His studies on tobacco smoke yielded results considerably higher than those obtained later by Sayers, [13] by Drinker, Thomson, and Finn,[14] and by Brown.[15] Baumberger found as much as 85 per cent retention of smoke. Sayers, working with tetraethyl lead in concentrations varying from 0.35 to 10.4 mg. per cubic meter of air, found that only 15 per cent was retained and attributed this limited retention to the small particle size. Brown's studies gave rather conclusive results, showing that the percentage retention is inversely proportional to the minute volume of air breathed and to the respiratory rate, whereas it is directly proportional to the particulate size, density of the dust suspended in air, and the extent to which the dust is wetted while passing through water. He found that retention was not affected by volume per respiration, vital capacity, or relative humidity of inspired air.

V. Dust Causing Pulmonary Fibrosis

A. SILICOSIS

1. History

Since ancient times it has been thought that dust caused disease. Perhaps the earliest reference to disease caused by dust and fume is that of Plinius,[16] who described the devices used by refiners to prevent the breathing of "fatal dusts."

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[12] J. P. Baumberger, *J. Pharmacol.*, **21,** 47 (1923).

[13] R. R. Sayers, *U. S. Bur. Mines Rept. Invest.* No. **2661,** 1924.

[14] P. Drinker, R. M. Thomson, and J. L. Finn, *J. Ind. Hyg.*, **10,** 13 (1928).

[15] C. E. Brown, *J. Ind. Hyg.*, **13,** 293 (1931).

[16] Caius Plinius Secundus, *Naturalis historia*, Bk. II. Trans. by K. C. Bailey under the title, *The Elder Pliny's Chapter on Chemical Subjects*, Pt. 1. Longmans, Green, New York, 1929.

[17] Georgius Agricola, *De re metallica*, Bk. I. Trans. from 1st Latin ed. of 1556 by H. C. Hoover and L. H. Hoover. Mining & Sci. Press, San Francisco, 1912.

In 1556, in *De re metallica*, Agricola[17] stated:

> On the other hand, some mines are so dry that they are entirely devoid of water and this dryness causes the workman even greater harm for the dust which is stirred and beaten up by digging penetrates into the windpipe and lungs and produces difficulty in breathing

The best of the early writings on silicosis is that of Ramazzini,[18] translated in 1705 in *A Treatise of the Diseases of Tradesmen*, in which he stated:

> For in hewing marble or stones out of the rock, in polishing and cutting them, they oftentimes suck in by inspiration the sharp, rough and cornered small splinters or particles that fly off; so that they are usually troubled with a cough, and some of them turn asthmatick and consumptive. . . . And in dissecting the corps of such artificers, the lungs have been found stuffed with little stones. Diemerbroeck gives a curious relation of several stone cutters that dy'd asthmatick, and were opened by him; in whose lungs he found such heaps of sand that in running the knife through the pulmonary vesicles he thought he was cutting some sand body. He adds that he was informed by a master stone cutter that in cutting stones there rises such a subtile dust, as is able to penetrate through ox bladders hung in the shop. . . . And this very dust he took to be the cause of the death of many unwary workmen.

In recent years the contributions to knowledge of silicosis have been sufficiently substantial, numerous, and varied to make this perhaps the most widely discussed occupational disease. Silicosis is of particular interest to students of preventive medicine not only because of its general distribution in industry but more particularly because of its tendency to increase susceptibility to tuberculosis—a characteristic inherent in the disease. The limited space of this chapter does not permit reference to many sound contributions which have led to our present understanding of dust disease. An exceedingly interesting and somewhat detailed review of the history of diseases caused by dust may be found in the work of Lanza.[19]

2. Exposure to Silica in Industry

Since siliceous material makes up the bulk of the earth's crust, it is not surprising to find silica exposures in industry, where raw materials from the earth are used to make many of the commodities necessary to our daily lives. Rocks and minerals are often intimately associated with free silica and it is obvious that those occupations concerned with mining, rock grinding, or drilling may constitute silicosis hazards, as well as occupations concerned with the processing and industrial use of siliceous products.

According to Knopf[20] the most common forms of free silica used industrially are massive crystalline quartz, quartzite, sandstone, flint, tripoli, diatomaceous earths and silica sand. Table 1, from Ladoo,[21] illustrates the great variety of uses to which silica is put in industry and indicates the kind of silica adapted to each purpose.

[18] B. Ramazzini, *A Treatise of the Diseases of Tradesmen*, English trans., 1705

[19] A. J. Lanza, ed., *Silicosis and Asbestosis*, Oxford Univ. Press, New York, 1938.

[20] A. Knopf, *U. S. Pub. Health Bull.* No. **187,** 1929.

[21] R. B. Ladoo, Silica, *Nonmetallic Minerals*, McGraw-Hill, New York, 1925, p. 523

3. Etiology of Silicosis

Silicosis has been defined by the Committee on Pneumoconiosis of the Industrial Hygiene Section of the American Public Health Association[22] as:

> A disease due to breathing air containing silica (SiO_2), characterized anatomically by generalized fibrotic changes and the development of military nodulation in both lungs and clinically by shortness of breath, decreased chest expansion, lessened capacity for work, absence of fever, increased susceptibility to tuberculosis (some or all of which symptoms may be present) and by characteristic x-ray findings.

The definition adopted at the International Silicosis Conference in 1930 and reaffirmed at the 1939 conference is generally accepted and is somewhat simpler than the above. It is as follows:

> Silicosis is a pathological condition of the lungs due to inhalation of silicon dioxide. It can be produced experimentally in animals.

Lanza[23] in "Etiology of Silicosis," as printed in the National Silicosis Conference Report on Medical Control, states:

> Simple of uncomplicated silicosis is a chronic, fibrotic disease of the lungs, due to the massive invasion of the pulmonary tissue by silica (SiO_2), inhaled in the form of dust. In its early stages silicosis may be symptom free; in its later stages shortness of breath, decreased chest expansion, lessened capacity for work, may—one or more—be present, together with an increased susceptibility to tuberculosis. The disease presents the characteristic x-ray appearance of nodulation, without which a clinical diagnosis may not be made.

The production of silicosis depends upon the following factors: the composition of inhaled dust, the number of particles of inhaled dust, the size of the particles of inhaled dust, the length of time during which particles are inhaled, and individual susceptibility.

a. Composition of Dust in Relation to Production of Fibrosis. The fact that silicosis is caused by free silica (SiO_2) is attested by the great mass of clinical experience as well as by experimental observations. Gye and Kettle[24] have shown that silica in solution, or in noncrystalline form, stimulates the proliferation of fibroblasts in tissues. Gardner[25] produced a reaction in the lungs of animals in a period as short as two years by exposure to extremely high concentrations of dust. Miller and Sayers[26] developed an intraperitoneal injection technique for testing the tissue response to dust, and their method has been used extensively by the United States Public Health Service. On the basis of this procedure it has been found that all dusts behave in one of three ways in the body tissues; they may disappear (be absorbed), cause cellular proliferation, or remain inert in the tissues.

[22] R. R. Sayers, *Am. Pub. Health Assoc. Yearbook,* 1932–33.

[23] A. J. Lanza, Report on medical control, National Silicosis Conference, *U. S. Dept. Labor, Div. Labor Standards, Bull.* No. **21,** Pt. 1 (1938).

[24] W. E. Gye and E. H. Kettle, *Brit. J. Expl. Pathol.,* **3,** 241 (1922).

[25] L. U. Gardner, in A. J. Lanza, ed., *Silicosis and Asbestosis.* Oxford Univ. Press, New York, 1938.

[26] J. W. Miller and R. R. Sayers, *U. S. Pub. Health Repts.,* **56,** 264 (1941), Reprint 2234.

TABLE 1

Industrial Uses of Silica and Types of Silica Used[21]

Uses	Types
Abrasives	
In scouring and polishing soaps and powders	Quartz, quartzite, flint, chert, sandstone, sand, tripoli and diatomaceous earth; all in finely ground state
In sandpaper[a]	Quartz, quartzite, flint, sandstone and sand; coarsely ground and closely sized
In sand-blast work	Quartz, quartzite, sandstone and sand, crushed into sharp angular grains uniform in size
Metal buffing, burnishing and polishing	Ground tripoli and other forms of ground silica
For sawing and polishing marble, granite, etc.	Sharp, clean sand graded into various sizes
As whetstones, grindstones, buhrstones, pulpstones, oilstones, etc.	Massive sandstone from very fine- to moderately coarse-grained
Tube-mill lining	Chert, flint and quartzite in dense, solid blocks
Lithographers' graining sand	Medium to fine sand or rather coarsely ground silica and tripoli
Tube-mill grinding pebbles	Rounded flint pebbles
In tooth powders and pastes	Various forms of pure silica finely ground
Wood polishing and finishing	All forms of silica ground to medium fineness
Refractories	
In making silica fire brick and other refractories	Fairly pure quartzite known as gannister; not less than 97 per cent SiO_2 nor more than 0.40 per cent alkalies, tightly interlocking grains desired
Metallurgy	
In making silicon, ferrosilicon and silicon alloys of other metals, such as copper	Moderately pure sand, massive crystalline quartz, sandstone, quartzite or chert
As a flux in smelting basic ores	Massive quartz and quartzite
Foundry-mold wash	Ground sandstone, quartz and tripoli
Foundry parting sand	Fine sand and ground tripoli
Chemical industries	
As a lining for acid towers	Massive quartz or quartzite
As a filtering medium	Massive diatomaceous earth and tripoli, sand, finely granular quartz or quartzite, finely ground tripoli, diatomaceous earth and other forms of silica
In the manufacture of sodium silicate	Pure pulverized quartz sand, pure tripoli and diatomaceous earth
In the manufacture of carborundum	Pure quartz sand

The immediate response of body tissue to any dust is essentially a foreign-body reaction, but the subsequent behavior of the tissue to any given dust determines whether such a dust is harmful.

TABLE 1 (*continued*)

Uses	Types
Paint	
As an inert extender	Finely ground crystalline quartz, quartzite and flint, also finely ground sandstone, sand and tripoli
Mineral fillers	
As a wood filler	Finely ground crystalline quartz, quartzite, flint, tripoli and other types of ground silica
In fertilizers	Finely ground silica of all types
In insecticides	
As a filler in rubber, hard rubber, pressed and molded goods, phonograph records, etc.	
In road asphalt surfacing mixtures	
Ceramics	
In the pottery industry as an ingredient of bodies and glazes	Flint, tripoli and chert, and other amorphous silica preferred; also all other forms of very pure silica, all finely ground
In the manufacture of ordinary glass	Pure quartz sand
In the manufacture of fused-quartz chemical apparatus, such as tubes, crucibles and dishes	Very pure massive quartz preferred
Decorative materials	
In the manufacture of gems, crystal balls, table tops, vases, statues, etc.	Rock crystal, amethyst, rose quartz, citrine quartz, smoky quartz, chrysoprase, agate, chalcedony, opal, onyx, sardonyx, jasper, etc.
Insulation	
Heat insulation for pipes, boilers, furnaces, kilns, etc.	Massive and ground diatomaceous earth
Sound insulation in walls, between floors, etc.	Massive and ground diatomaceous earth
Structural materials	
Sand-lime brick	Moderately pure, sharp, angular sand, preferably finer than 20-mesh, together with a small percentage of finely pulverized silica
Optical quartz	
For the manufacture of lenses and accessories for optical apparatus	Clear, colorless, flawless rock crystal or massive crystallized quartz

[a] Many such papers use artificial abrasives today.

In the peritoneal injection experiments of Miller and Sayers only dust containing free silica caused fibrous proliferations.

Although it has been well established that silicon dioxide is the cause of silicosis, there has been little satisfactory explanation for its action. Earlier it was thought that the fibrous nature of the proliferation was related to the hardness or sharpness of the particles. However, Gardner[27] found that no fibrosis was produced by experimental inhalation of aluminum oxide and diamond dusts which are even harder and sharper than silica. Thus, the action is clearly chemical, but the exact chemicophysiological reaction that takes place is still unknown.

The mixed reaction sometimes produced by dusts of the inert group in which silica is mixed with other minerals emphasizes the possible effect of mixed dusts on the development of silicosis. The probable importance of concomitant exposures has also been indicated by clinical experience. Chapman,[28] MacDonald and his associates,[29] and Kilgore[30] have reported cases of rapidly developing silicosis caused by breathing air with high concentrations of silica and alkali dust. Kettle[31] and McCord[32] failed to demonstrate such action experimentally. McCord, on the basis of extensive investigations of workers in six plants where there was exposure to silica and alkali dusts, found no evidence of an accelerator action by alkalies. In fact, the absence of silicosis in this group suggested an inhibitor action which he believes may have resulted from the marked increase in solubility of silica in the presence of alkali. Peritoneal injection in animals yielded no results to prove either an accelerator or inhibitor action of alkali in the formation of silica nodules. Alkali did, however, cause the silica to spread from the point of injection and increased its primary toxicity.

The absence of silicosis in ganister-brick manufacturing was thought at first due to an inhibiting effect of accompanying dusts; more recently it has been found that the concentration of free silica in the work atmosphere was too low to cause fibrosis. Silicosis as found in coal miners (anthracosilicosis) and in foundry men may be quite different in x-ray appearance and in its course from that observed in quartz grinders.

b. Number of Particles Inhaled in Relation to Production of Fibrosis. It is apparent that the type of dust may play an important part in determining the number of particles in the workroom atmosphere. Not only may some components of admixtures flocculate and thus change the character of a dust, but silica itself, being a hard material with a tendency to form large particles as compared with those formed by softer minerals, may settle out more quickly than other components of a mixed dust.

However, at this point we are somewhat more concerned with the concentrations of dust that are harmful than with the factors that have produced any given concentration in the air. Determinations of free and total silica in the lungs of patients who have died after fibrosis developed and in those without fibrosis have been made by incinerating the lungs and chemically analyzing the ash for its silica content. Although there have been some variations in published data on the amount of silica in pulmonary tissue necessary to produce silicosis, Sladden,[33] McNally,[34] Badham and Taylor,[35] and Fowweather[36] found fairly comparable amounts. Drinker and Hatch[2] sum up the present knowledge somewhat as follows: as a rough guide, a total silica content as high as 0.2 per cent of dried lung can be considered normal. A content over 1 per cent is definite evidence of dust exposure, and this amount is usually accompanied by fibrosis. There are too much overlapping of data and variation in technique to be sure from published data of the significance of quantities between 0.2 and 1 per cent of ashed lung. This fact is of especial significance, as pointed out by Cummings.[37] Since there is usually no evidence of silicotic reaction in lungs containing less than 1.5 to 2 g. of silica (1 per cent of weight of dried lung), it may be inferred that the contraction of silicosis does not necessarily follow the inhalation of silica. Silicosis occurs only after the inhalation of amounts in excess of a minimum.

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[27] L. U. Gardner, *Am. Rev. Tuberc.*, **20**, 883 (1929).

[28] A. M. Chapman, *J. Am. Med. Assoc.*, **98**, 9 (1935).

[29] G. MacDonald, A. P. Piggot, and F. W. Gilder, *Lancet*, **2**, 836 (1930).

[30] E. S. Kilgore, *J. Am. Med. Assoc.*, **99**, 1414 (1935).

[31] E. H. Kettle, *Proc. Inst. Mining Metallurgy (London)*, *43rd Sess.*, 1934.

[32] C. P. McCord, *Ind. Med.*, **5**, 17 (1936).

In any control program we are of course concerned primarily with the amount of dust in the air that will cause fibrosis. The methods of determining atmospheric dust concentrations are discussed in Chapter VII. Cummings suggested that atmospheric concentrations of silica dust should be considered in terms of two thresholds: the primary threshold, a level at which a healthy man can be employed for his lifetime without harm, about 5 million particles per cubic foot (light-field count); and the secondary threshold, a level at which a healthy man will inevitably develop silicosis, about 100 million particles per cubic foot (light-field count). The National Silicosis Conference summarizes the situation as follows: "There is evidence that for prolonged exposure a concentration of more than 5 million particles per cubic foot, of a highly siliceous dust, is dangerous. Therefore it is now considered good practice to hold concentrations of highly siliceous dust at 5 million particles per cubic foot, or less," as based on light-field counting methods.

Since standards of safe atmospheric dust concentration based on medical findings have been suggested tentatively for only a few industrial dusts, and since considerable study is necessary to form a basis for such standards for other industrial dusts, a tentative arbitrary measure of what is good practice may be used. This should be within the limits of good engineering practice and yet low enough to control the silicosis hazard for most industrial exposures. The following formula is frequently used to express the maximum permissible concentration of silica in the air:

> Multiply the percentage of free silica by the total dust particle count per cubic foot (light-field technique). If the result is over 5 million, the concentration may be considered too high. For example: a dust containing 10 per cent free silica with an average total concentration of

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[33] A. F. Sladden, *Lancet*, **2**, 123 (1933).

[34] W. D. McNally, *J. Am. Med. Assoc.*, **101**, 584 (1933).

[35] C. Badham and H. B. Taylor, *Med. J. Australia*, **1**, 511 (1933).

[36] F. S. Fowweather, *Chem. Industries*, **53**, 713 (1934).

[37] D. E. Cummings, "The Etiology of Silicosis," in B. E. Kuechle, ed., *Fourth Saranac Laboratory Symposium on Silicosis*. Employers Mutual Liability Insurance, Wausau, Wis., 1939.

30 million particles per cubic foot would give 0.10 times 30 million, which equals 3 million (good practice); a dust containing 30 per cent with an average total concentration of 50 million particles per cubic foot would equal 0.3 times 50, or 15 million (unsatisfactory). This formula is not applicable to any dust containing less than 5 per cent free silica.

The Division of Occupational Health, U. S. Public Health Service,[38] has suggested that an attempt should be made to have highly silieeous dusts kept at a concentration below 4 million particles per cubic foot since considerable silicosis occurred in the pottery industry even with low dust concentrations.

Dust may also be simply a nuisance. It is considered good practice to control even relatively harmless dust sufficiently to prevent concentrations in excess of 50 million particles per cubic foot (by light-field count) in the workroom air.

c. Particle Size in Relation to Development of Fibrosis. We have already mentioned the fact that large particles settle more rapidly than small ones and that particle size is important as a determining factor in the actual amount of dust in air. Particle size is even more important in determining the chemical activity of the dust and physiological responses to it. Chemical activity is, of course, increased in small particles because of the increased surface area. McCrae[39] found that 70 per cent of the particles in silicotic lungs were less than 1 μ in diameter and that the largest were not greater than 10.5 μ. An upper limit of 10 μ as the maximum size that will produce silicosis has been suggested because larger particles are probably collected by mucus in the upper respiratory tract and moved out of the lungs by ciliary action. The importance of small particles in the production of fibrosis has been well demonstrated by Tebbens, Schulz, and Drinker.[40] These investigators produced liver fibrosis in experimental animals by intravenous injections of suspended silica and found that particles less than 0.6 μ in diameter caused much more fibrosis than larger particles.

Briefly, silicosis is caused by the inhalation of silica particles less than 10 μ in diameter. Recent work suggests that particles of less than 0.6 μ may be of greatest importance in this respect.

d. Individual Predisposition. Detailed discussion of the role of individual predisposition in the etiology of silicosis is hardly necessary. Race and sex seem to play little part, although race may be a factor in the development of tuberculosis just as financial status may be a factor. Certainly it is known that of two persons working in the same dusty exposure one may contract silicosis in a few years while the other may require many years. We have already mentioned the possible influence of differences in nasal filtration as a factor in causation of silicosis. It is likely that there are sound explanations for the many variations in individual susceptibility, but clarification is lacking. Many of these variations undoubtedly are related to differences in adrenal cortical hormone activity.

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[38] R. H. Flinn, W. C. Dreessen, T. I. Edwards, E. C. Riley, J. J. Bloomfield, and R. R. Sayers, *U. S. Pub. Health Bull.* No. **244**, 1939.

[39] J. McCrae, *Pub. S. African Inst. Med. Research*, Report No. 3 (1913).

[40] B. D. Tebbens, R. Z. Schulz, and P. Drinker, *J. Ind. Hyg. Toxicol.* **27**, 199 (1945).

4. Pathological Anatomy and X-ray Findings

a. Benign Pneumoconiosis. All dust other than that containing free silica and asbestos generally is inert and produces little or no fibrosis in the lungs.

X-ray examination. There is simply an accentuation of the normal, branching, treelike shadows cast chiefly by the pulmonary blood vessels. As an occasional variation in this picture there may be superimposed fine reticulations. These reticulations are thought to be caused by thickening of the sheaths of the pulmonary arteries and thickening of the interlobular septa (see Figures 4 and 5).

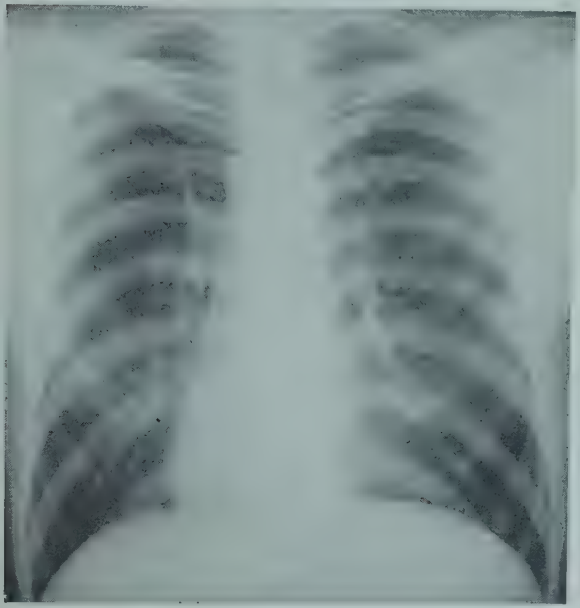

Figure 4. *Normal adult chest.* Note that root shadows and vascular markings are not prominent. Underexposed films may cause exaggeration of the vascular pattern and suspicion of dust retention.

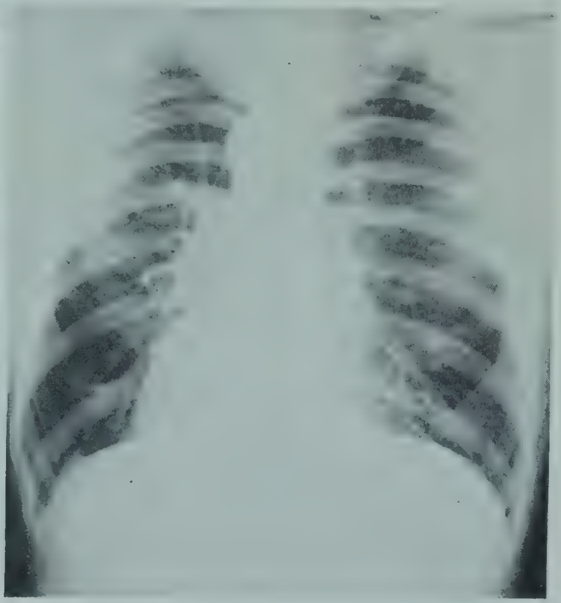

Figure 5. *Increased linear markings.* These usually are due to increased vascularity of the lungs for one reason or another and are not diagnostic of silicosis or other fibrosis. They may, however, be due to early inert dust retention in the lymphatics of the lungs.

Dusts with higher atomic weights, such as iron (56), tin (119), and barium (137), are at times retained in the lungs to such a degree that the perivascular and peribronchiolar collections of the dust actually cast nodular shadows on chest x-ray films. This was first shown by Enzer and Sander[41] in 1938 in the postmortem tissue studies of an electric arc welder, and was subsequently confirmed by animal experimental studies by Hamlin and Vorwald.[42] Such iron deposits showed no evidence of fibrosis or other cellular response. The same has been shown to be true for barium and tin deposits.[43]

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[41] N. Enzer and O. A. Sander, Chronic lung changes in electric arc welders. *J. Ind. Hyg. Toxicol.,* **20,** 333–350 (May, 1938).

[42] L. E. Hamlin and A. J. Vorwald, Siderosis: a benign pneumoconiosis due to the inhaiation of iron dust, *Ind. Med. and Surg.,* **19,** 151–180 (April, 1950).

Gross examination. Except with prolonged and intensive exposure, the pleural surfaces of lungs with benign pneumoconiosis show only focal and linear collections of pigment that are soft in consistency and not raised above the surrounding tissues. On cut surfaces, gross examination reveals rounded flecks of pigment 2 to 3 mm. in diameter, but a lens shows finer linear deposits in the interlobular septa and in the outer walls of the blood vessels. The entire lung may be colored by pigment as in the black lung of soft-coal miners, but no fibrosis is found unless there has been exposure to free silica. There may be small patches of emphysema in or adjacent to pigmented areas. Scars of healed infections differ from the usual scars by the presence of pigment.

Microscopic examination. If death occurs during exposure, dust particles are found free in the peripheral air spaces or ingested by alveolar phagocytes that are found adherent to alveolar walls and in loose areolar tissue about the blood vessels, especially the arteries, and in the interlobular septa. These last two linear deposits are referred to as perilymphatic deposits because of their close relationship to the lymphatic trunks. The bronchi show relatively little dust; when any is present, however, it is found in the connective tissues just beneath the epithelium. If there has been no recent exposure (years), the intrapulmonary dust tends to be removed from the air spaces and deposited along the lymph trunks; in severe exposure large amounts of dust-filled phagocytes may remain in the alveoli. Nearly all pure substances other than silica cause little cellular reaction. Coal and some silicates, especially mica, may cause minor irritation without producing fibrosis. Unless the linear reaction is fibrous and caused by free silica, there is no altered susceptibility to tuberculosis.

b. Discrete Nodular Silicosis: X-ray examination. This form of dust disease is characterized in the x-ray film by enlarged and dense hilum shadows and small discrete nodular shadows, uniformly distributed throughout all parts of both lungs, with the possible exception of small emphysematous areas in the costophrenic region. In the absence of infection, the nodules are of uniform size, usually not exceeding 4 mm. and seldom more than 6 mm. in diameter. The nodules are sharp with well-defined borders (see Figure 6).

Gross examination. The pleurae are studded with slightly elevated, grayish nodules 2 to 3 mm. in diameter, and around these there may be a flat zone of black, gray, or brown pigment. Pleural adhesions may or may not be present. The lungs are stiffer than normal but crepitus is present. There are palpable shotty nodules. The cut surfaces are seeded with black or gray nodules, 2 to 4 mm., or

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[43] A. Arrigoni, Pneumoconiosi da bario, *Med. d. lavoro*, **24**, 461–468 (1933); E. P. Pendergrass, Roentgen diagnosis of pneumoconiosis and silicosis, *Am. J. Roent. and Rad. Ther.*, **48**, 571–594 (1942) (Baritosis, p. 580); E. P. Pendergrass and A. W. Pryde, Benign pneumoconiosis due to tin oxide, *J. Ind. Hyg. Toxicol.*, **30**, 119–123 (1948); F. Barták, M. Tomečka, and O. Tomíček, Stannosis, *Časop. lék. česk.*, **87**, 915–932 (1948); C. C. Dundon and J. P. Hughes, Stannic oxide pneumoconiosis, *Am. J. Roent. and Rad. Ther.*, **63**, 797–812 (1950).

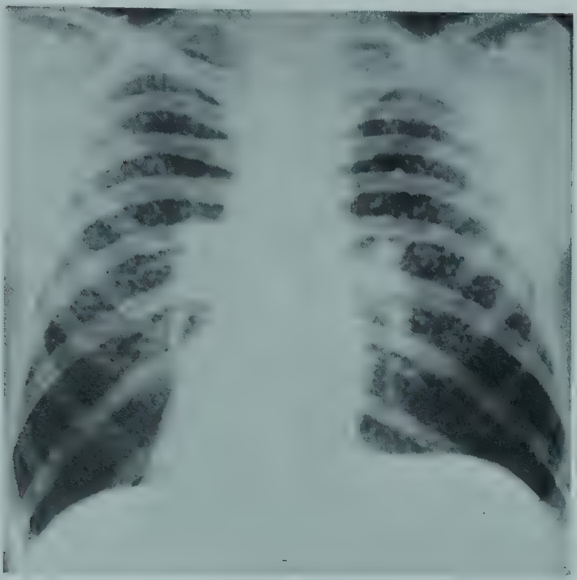

Figure 6. Classical nodular *silicosis* of moderately well-developed degree in sandstone wheel grinder. Only slight shortness of breath on exertion. Note large and dense root shadows.

rarely 6 mm., in diameter. The edges of the nodules are well defined, but a lens shows pigmented strands radiating from their periphery. There is little confluence except where scars or infection are present. Gross emphysema may or may not be present, but this condition may be apparent only with microscopic examination. For differentiation from perilymphatic pigmentation there must be definite pleural nodulation in an appreciable amount. Some nodules may arise along the peripheral branches of the pulmonary arteries. The tracheobronchial lymph nodes are at first enlarged and firm, later smaller and extremely hard. Sections of these nodes reveal dense leatherlike tissue, which is silky in texture because of the decrease in collagenous connective tissue.

Microscopic examination. Microscopic examination shows layers of dense hyaline collagenous fibers with nuclei so compressed as to be almost invisible at times. The borders are clear cut, with no exudation. There may be pigment either about the periphery or in focal points within the nodule itself. The nodule may be calcified, occasionally to the point of bone formation in its central portion. Nearly all nodules are associated with branches of the pulmonary arteries, as demonstrated by wax reconstruction of the arteries; they may form spherical or spindle-shaped masses around the arteries. Pigmentation occurs about the lymphatic trunk just as in nonspecific pneumoconiosis, but there is always some fibrosis. The air spaces immediately adjacent to the nodules are distorted and frequently dilated. There may or may not be emphysema. The alveolar walls between nodules may be entirely normal.

c. *Modified Silicosis.* Modified nodulation results from breathing dust containing free silica mixed with other minerals. Although a great deal is not known about mixed dust reactions, there have been sufficient examinations of the lungs of hard-coal miners to determine that lung tissue responds differently to the dust of coal mines than to pure silica dust.

X-ray examination. Long experience in interpretation of roentgenograms of silicotics with varied exposures may enable one to conjecture with a reasonable degree of accuracy the general type of exposure. Large amounts of nonsiliceous or silicate dust in the mixture tend to induce perilymphatic deposits of the linear type. Free silica intensifies this reaction and causes it to become fibrous. At times hyaline nodulation occurs, perhaps when there is enough free silica in the dust, but this reaction is atypical. Gross examination of the modified silicotic nodules may reveal heavy deposition of pigment with or without dense fibrosis. With a hand lens hard elevated nodules may be seen in the centers of some of the pigment deposits (see Figures 7, 8, 9 and 10).

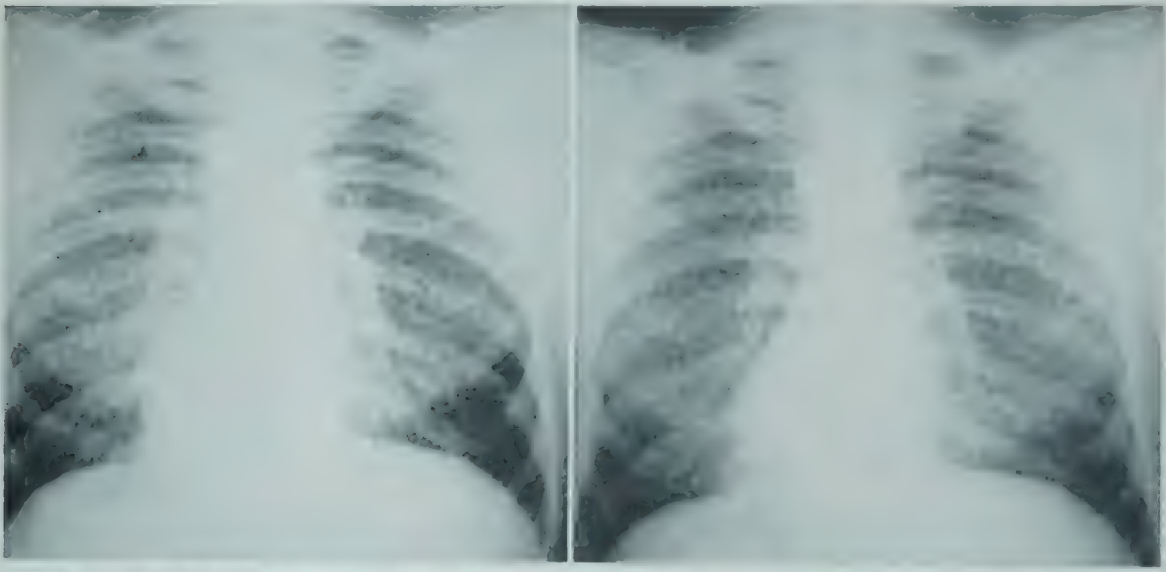

Figure 7. *Siderosis* in electric welder (many years in confined areas and never silica dust exposure). Note normal root shadows and absence of changes in nine-year interval. He is still working as foreman in weld shop in 1955 without chest symptoms; has refused re-x-ray since 1944. (Left, 1935; right, 1944.)

Microscopic examination. On microscopic examination it will be seen that many of the nodules consist of nothing but coarse, heavily pigmented fibers devoid of organized arrangement. Such nodules may have irregular peripheral extensions, which fuse with those of others. (This fusion of nodules may be partly responsible for the appearance produced in the conglomerate reaction.)

d. Nodular Silicosis with Localized Conglomerate Lesions: X-ray examination. X-ray examination shows isolated or bilaterally symmetrical massive shadows usually located in the upper half of the lungs but sometimes in the lower third. These massive shadows may extend from the root to the pleural surface, or they may lie deep in the parenchyma. Serial x-rays may show that the lesions remain stationary over a period of many years or they may show an increase in

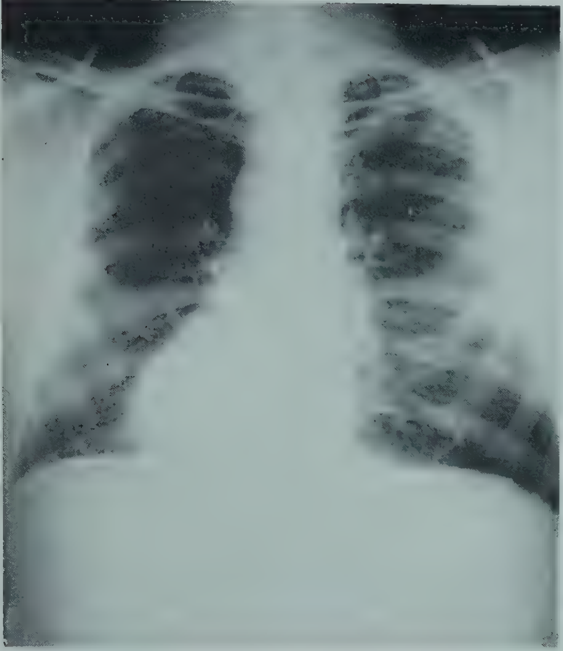

Figure 8. *Siderosilicosis* in grinder in foundry cleaning rooms for twenty-five years. Note minimal discrete nodulation and rather small root shadows. No chest symptoms.

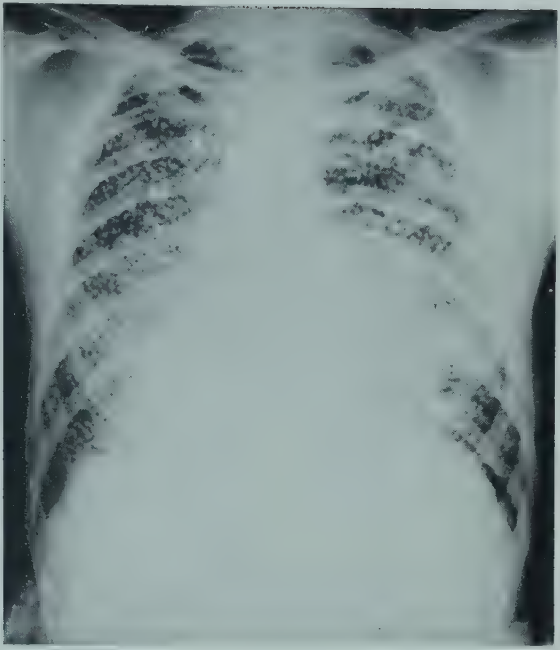

Figure 9. *Baritosis*. Barium oxide powder exposure for many years. Never shortness of breath or other symptoms referable to the chest. (Courtesy Dr. E. P. Pendergrass.)

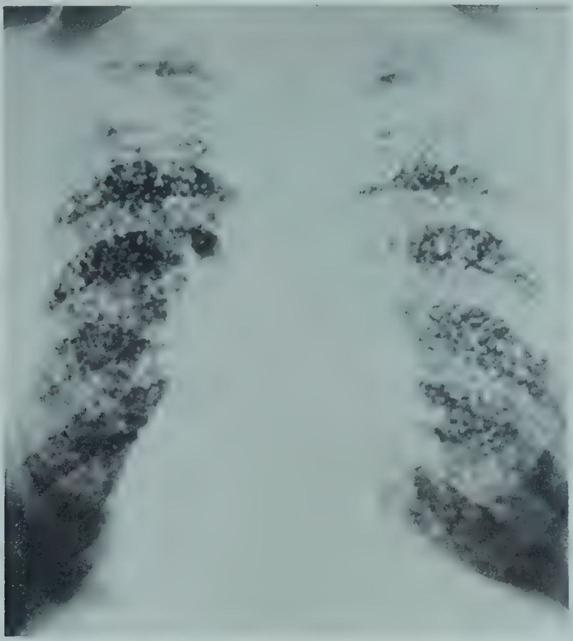

Figure 10. *Stannosis*. Tin oxide powder exposure for many years. No shortness of breath or other symptoms referable to the chest. (Courtesy Dr. J. B. Stocklen.)

size on successive films. Ultimately central rarefaction, interpreted as cavitation, may develop with subsequent evidence of infection in other parts of the lung. Gardner[44] presents the following working hypotheses with regard to conglomerate lesions:

> 1. In silicotuberculosis the infection may heal so completely that its tuberculous origin is no longer recognizable. Such an outcome has been observed in experimental animals exposed to ferruginous chert and infected with attenuated tubercle bacilli.
>
> 2. Conglomerate lesions in the upper lung fields, particularly when they are bilateral, are in the great majority of cases due to an underlying tuberculosis in healed or latent form. In persons not exposed to dust, bilateral disease in this location proves to be tuberculous in 95 to 98 cases out of every hundred, and even unilateral disease can safely be considered tuberculous in 90 per cent of cases.
>
> 3. Large isolated or bilaterally symmetrical conglomerations in the lower lungs should be considered tuberculous unless this origin can be excluded. In that case the possibility of organizing pneumonia due to Friedlander's bacillus or other organisms should receive consideration.
>
> 4. The character of the fibrosis resulting from the combined activity of an infectious organism and silica dust with or without other minerals may suggest a relationship between the time of exposure to dust and the development of the infection.
>
> (a) When the silicosis is already established before tuberculosis supervenes the infection localizes in and about the nodules which retain their form but increase in size. Bronchial obstruction *caused by the infection* may produce widespread atelectasis with a consequent approximation of the nodules in the involved area. In such cases the outlines of large, individual nodules in the resultant conglomeration are distinct and clearly defined.
>
> (b) When silicosis and chronic tuberculosis have developed simultaneously the nodular character of the conglomerate fibrosis is less obvious. Nodules are present but they are surrounded by a matrix of more diffuse fibrosis produced by the action of the silica upon an organizing pneumonic process.
>
> (c) When the scars of a healed infection are already present before employment in the dusty industry, the inhaled particles accumulate in particularly large quantities in their immediate vicinity. Continued accumulation in the localized area produces many nodules, which are small because they are closely packed together but typically spherical in outline because there is no activity in the underlying infectious process to produce diffuse fibrotic reaction.

Many patients with conglomerate silicotic fibrosis are dyspneic, but the toxic symptoms of the associated infection may be absent. This is reasonable, since healed tuberculosis does not cause symptoms and even active infections may be so well encapsulated by dense fibrous tissue that no tissue reaction is possible.

5. Silicotuberculosis

The relationship between silica exposure and the development of tuberculosis has been well demonstrated in the United States as well as in other countries where there has been such exposure. One of the most remarkable demonstrations of the relation of tuberculosis to silica dust exposure is found in the work of Mavrogordato,[45] illustrated graphically in Figure 11.

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[44] L. U. Gardner, "Pathological Anatomy," in B. E. Kuechle, ed., *Fourth Saranac Laboratory Symposium on Silicosis*, Employers Mutual Liability Insurance, Wausau, Wis., 1939.

[45] A. Mavrogordato, *Pub. S. African Inst. Med. Research*, Report No. 19 (1926).

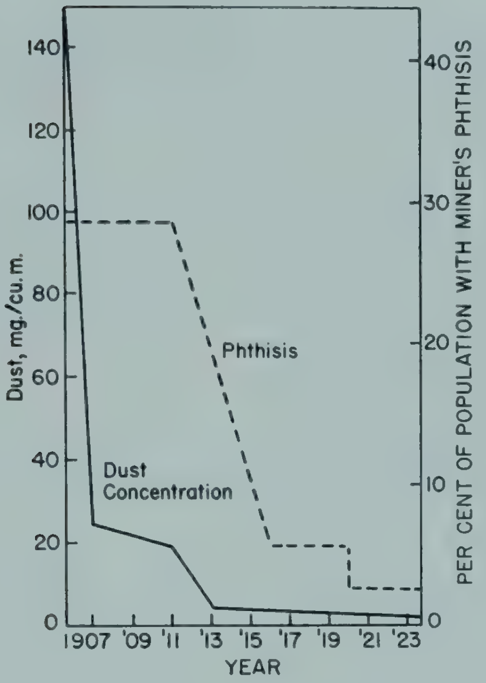

Figure 11. Dust control and silicosis in South Africa.

The symptomatology and clinical findings in silicosis and in silicosis complicated by tuberculosis (Figure 12) have been summarized in the National Silicosis Conference Report of the Committee on Medical Control and these have been condensed by Lanza[19] as follows:

SUBJECTIVE SYMPTOMS: *Dyspnea.* The complaint most frequently mentioned is shortness of breath. Depending upon the extent of the involvement, this varies from slight

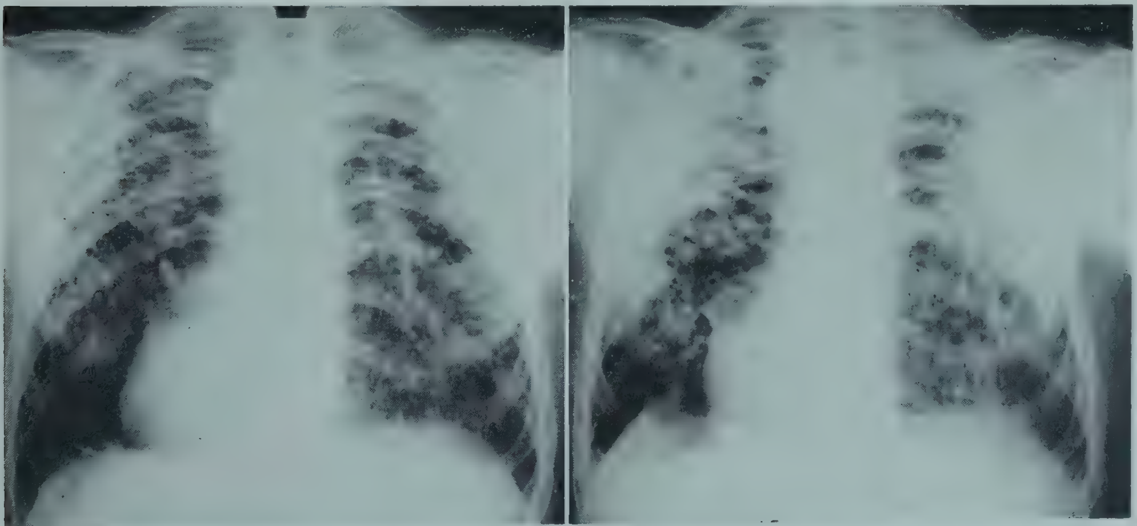

Figure 12. Progressive *silicotuberculosis* and emphysema, with tubercle bacilli never found in numerous sputum and gastric cultures. Marked dyspnea and impaired lung function. Patient died in 1948 of right heart failure.

dyspnea, following exertion, to marked dyspnea upon the least exertion or even when at rest. The shortness of breath noted in advanced silicotics presents one peculiarity in that it is seldom accompanied by orthopnea, the individual being no more short of breath lying down than when in an upright position. This may not be so, however, when silicosis is complicated by cardiac disease or by true asthma.

Silicosis	Silicosis with infection
If present at all, noted as a rule only after sudden or extra exertion. Seldom so marked as to interfere with routine duties. However, in cases with extensive pulmonary fibrosis, it may limit the individual's activities	If complicating infection is not widespread, may be no more marked than in cases of simple silicosis but as infection and fibrosis increase, it becomes disabling.

Cough. Many silicotics complain of a troublesome cough. This cough differs from that resulting from simple irritation due to dust which clears up upon removal from exposure. When present, it is more pronounced in the morning or upon beginning work after a rest period.

Silicosis	Silicosis with infection
The typical silicotic cough is dry and nonproductive. It usually parallels shortness of breath in degree and may contribute to disability.	The cough usually becomes more troublesome and is productive. The sputum varies from thick, tenacious, mucous material to that of a foul, purulent or purohemorrhagic consistency. Microscopic examination or animal inoculation frequently reveal tubercle bacilli or, in some cases, organisms of the fusiform spirochetal group. In advanced cases, coughing attacks are often of such severity as to leave the individual exhausted.

Chest Pain. This symptom is complained of by a majority of silicotics. It varies from a feeling of tightness in the chest to the sharp pain typical of pleurisy. (Since chest pain is offered as a complaint in many conditions, it cannot be stressed as especially characteristic of silicosis.)

Silicosis	Silicosis with infection
A late symptom in cases of simple silicosis. Then seldom more than a sense of tightness or feeling of substernal pressure.	Pleuritic pain is suggestive of a complicating infection. It is increased by exercise and by coughing and may be distressing in advanced cases with extensive infection.

Hemoptysis. True hemoptysis seldom occurs. Frequently, however, the sputum may be blood-streaked following a severe coughing attack. Hemoptysis must always be considered as suggestive of tuberculosis.

Silicosis	Silicosis with infection
Occasional blood-streaked sputum. May result from alveolar rupture following sudden exertion in advanced cases.	May be the first indication of tuberculous infection. May be consequent upon the development of pneumothorax. May occasionally be excessive if cavities are present.

General Complaints. Weakness, loss of weight, digestive disturbances, night sweats, insomnia, dizziness, and edema of the extremities are not characteristic of uncomplicated silicosis but are apt to be present if infection supervenes, especially when the infection becomes extensive.

OBJECTIVE SYMPTOMS: Changes in the general appearance are infrequent in simple silicosis unless far advanced. Such changes as are manifested are usually due to complicating conditions.

Silicosis	Silicosis with infection
Early cases appear unchanged; in fact, it is common to find these individuals showing a slight increase in weight, possibly because they are less active. As the disease progresses, respiratory embarrassment is noticeable and there is a general loss of muscle tone.	The appearance sooner or later becomes that of chronic phthisis. The bony landmarks of the thorax become prominent and there is an increase in the anterior-posterior diameter of the chest, possible hypertrophy of the accessory respiratory muscles of the chest, and in the final stages, retraction of the supra and infra clavicular spaces. Cyanosis and clubbing of the fingers are not prominent except in those cases of long standing, with cardiac disturbances.

Chest Expansion. Decrease in the expansion of the chest may be demonstrated in cases with extensive pulmonary fibrosis.

Silicosis	Silicosis with infection
In early cases it is usually not possible to demonstrate decreased expansion. In advanced cases, expansion may be lessened by 20 to 30 per cent but remains equal on both sides.	Decrease in expansion may not be noted in early silicosis with slight infection but as the condition progresses, a definite decrease is readily observed. When infection is more pronounced in one area of the lung, expansion may be more markedly decreased on the affected side, particularly if there is pleural involvement.

Prolonged Expiration. In most cases, decreased chest expansion is preceded and later accompanied by a definite change in respiratory rhythm. Close observation reveals that even at rest there is a distinct tendency to prolongation of the expiratory phase, which, as silicosis advances, becomes more marked. Following exercise, the silicotic may breathe less rapidly than the normal person under similar conditions as the lungs cannot be emptied rapidly enough to permit more rapid respiration; but although the respiratory rate is not so rapid as in the normal person, it will persist for a longer period.

Silicosis	Silicosis with infection
Early in the development of a simple silicosis, prolonged expiration may be evident only after exertion. Later the degree of prolongation usually parallels the increase in pulmonary fibrosis.	In cases of early silicosis with slight infection, prolongation of the expiratory phase may be no more marked than in simple silicosis. As the condition progresses and fibrosis increases, it may simulate characteristic asthmatic respiratory rhythm.

Signs Revealed by Palpation of the Chest. Except in the late stages of silicosis with infection, little is revealed by palpation of the chest. However, where there is a measurable decrease in expansion, one may note by palpation that, upon forced inspiration, the anterior chest wall is lifted forward by the accessory muscles of respiration.

Silicosis	Silicosis with infection
No change noted until extensive fibrosis has taken place, when there may be an increase in tactile fremitus generally.	When infection is extensive, tactile fremitus is increased and occasionally friction rubs may be elicited. Extensive thickening of the pleura or pneumothorax may result in a decrease or absence of tactile fremitus over affected areas.

Percussion. There is usually an impairment of the percussion noted over the whole chest but unless one is particularly observant, this may not be detected.

Silicosis	Silicosis with infection
Since impairment in resonance is general over all lung areas, it is difficult to demonstrate until advanced fibrotic changes have developed. Decrease in diaphragmatic excursion may sometimes be revealed by percussion.	Increase in loss of normal resonance. When massive areas of fibrosis have developed, this may amount to absolute dullness over areas involved. Amphoric resonance may be elicited where there is pneumothorax. Decreased diaphragmatic excursion may readily be shown in advanced infection.

Auscultation. Breath sounds are usually decreased in intensity and the characteristic prolongation of expiration is readily noted.

Silicosis	Silicosis with infection
Decrease in breath sounds general and more marked as the condition progresses. Subcrepitant râles, which clear up after coughing, are occasionally heard.	Usually heard, some of the following: Persistent post-tussic crepitant and subcrepitant râles; coarse rhonchi associated with productive coughing, wheezing or musical râles increased by exertion and coughing, amphoric breath sounds over cavities and areas of pneumothorax; pleural friction rubs occasionally.

Part of the symptomatology associated with silicosis may be due to pathological processes other than fibrosis. Filley, Hawley, and Wright,[16] using isolated perfused lungs of guinea pigs found that colloidal silica produced bronchial constriction, although soluble silica did not. This at least suggests that part of the disability in silicosis may result from bronchial constriction. The inability of soluble silica to cause bronchial constriction, however, raises a question as to the validity of the assumption that this same reaction occurs in workers exposed to silica.

6. Diagnosis of Silicosis

To make a definite diagnosis of silicosis, each of these three criteria must be fulfilled: (*1*) history of adequate exposure to dust containing free silica in particle sizes below 10 μ; (*2*) exposure to such dust over a period of years, depending on the concentration of free silica in the dust; (*3*) a nodular x-ray pattern with the root shadows enlarged and increased in density. The history of exposure has become of increasing importance because of the many other conditions that now are known to simulate nodular silicosis by x-ray. Hamlin[47] has found more than twenty conditions or diseases that cannot be differentiated from silicosis by x-ray alone.

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[16] G. F. Filley, J. G. Hawley, and G. W. Wright, *J. Ind. Hyg. Toxicol.*, **27**, 57 (1945).

In evaluating the past dust exposures, it is essential to start with the very first gainful employment, including part-time jobs during the school years. Many instances could be cited of significant dust exposures on such part-time jobs in the distant past that were the only explanation for x-ray lung changes found much later in life. Also, precise details of each occupation must be covered. It is not enough, for example, to elicit a history of foundry work in the past. It is important to determine the type of foundry, the type of castings poured, the size of the castings, the method of cleaning the castings, and the precise occupation in the foundry. It is not enough even to know that one of the past jobs was grinding. Where was the grinding done? Any other jobs in that area that caused dust or fume exposure? If so, what were they? What type of castings were being ground? How had they been cleaned before grinding? What abrasive was used in the grinding wheels? The only dusts to which iron and steel grinders may be exposed when their castings are free from molding sand are iron and the artificial abrasive, aluminum oxide, in which case they could not have silicosis. Silicon carbide (SiC), which is carborundum, may be mildly fibrogenic, but aluminum oxide never is.[48]

Even after the most detailed occupational history and x-ray film evaluation, it occasionally is impossible to differentiate silicosis from sarcoidosis. It then becomes necessary to make special tests for sarcoidosis, such as serum protein determinations to see if the a/g ratio is reversed, the Kveim skin test, and liver function tests. Even these may be inconclusive, in which case a surgical lung biopsy must be resorted to. These have been done with increasing frequency in recent years. Danger of complication is practically nil, and the results usually are conclusive when the surgeon makes a careful selection of an involved area.

7. *Evaluation of Disability in Silicosis*

a. Statement of the Problem. To both management and labor, silicosis at one time was nearly synonymous with total disability. It has now become clear that uncomplicated, first-stage, discrete, nodular silicosis is notorious for its lack of symptoms. Even relatively advanced stages of silicosis may be unaccompanied by disability. In fairness to both employer and employee, it is necessary to go beyond simple diagnosis. In examining a patient with roentgenographic evidence suggesting silicosis, an attempt must be made to answer certain questions. Does he have a history of sufficient exposure to free silica dust to account for the roentgenographic changes present? Does he have complicating tuberculosis or other infection? Is he incapacitated or disabled by his condition? The first two of these questions are usually answered by the examining physician. The real problem is the third question. Is the man disabled? An incorrect answer will cause injustice to employee or employer. In the past, attempts to solve the disability problem in silicosis were based chiefly upon the clinical approach and roentgenographic studies. For obvious reasons, clinical appraisal of a given individual's pulmonary disability is limited to objective signs and principally to observation at rest and during the performance of exercise tests. Roentgenographic studies, in addition to determining the stage or extent of disease, were used to ascertain the presence or absence of emphysema. Currently, physicians are eagerly accepting the objective assistance offered by pulmonary function tests. The use of these more accurate aids must be accompanied by knowledge of their limitations. One of the major unsolved problems is the degree of dysfunction beyond which all individuals will be disabled. Do individuals with simple nodular silicosis have more disabling emphysema than persons in the general population without silicosis? It is probable that satisfactory answers must await lung function testing of large groups of people with and without silicosis.

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[47] L. E. Hamlin, Chest conditions simulating silicosis, *Ind. Med.*, **15**, 376–381 (1946).

[48] O. A. Sander, Foundry workers' pneumoconiosis, *Arch. Ind. Hyg. and Occupational Med.*, **10**, 512–521 (December, 1954).

b. Pathologic Physiology and General Principles. Based upon recent significant studies,[49–52] the following simple classification of the types of pulmonary insufficiency is useful: *(1)* ventilatory pulmonary insufficiency, which is concerned with defective air movement into and out of the lungs; *(2)* distribution difficulty, which is concerned with alveolar ventilation and perfusion relationships; *(3)* diffusion difficulty, which is concerned with passage of carbon dioxide and oxygen between capillary and alveolus; *(4)* circulatory insufficiency, which is concerned with reduction in the absolute size and distensibility of the pulmonary vascular bed.

Ventilatory insufficiency.[53] Silicosis may interfere with pulmonary ventilation in several ways. By simple proliferation, it may encroach upon the space that would normally be occupied by functioning lung tissue. Fibrous tissue that undergoes shrinkage may give rise to overdistension of adjacent normal lung tissue. The degree to which the involved portions of the lung can be expanded will be limited. It is possible that by suitable location it may also limit the expansibility of interposed normal lung tissue. There may be interference with air flow by

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[49] G. W. Wright, Disability evaluation in industrial pulmonary disease, *J. Am. Med. Assoc.*, **141**, 1218–1222 (1949).

[50] H. L. Motley, The use of pulmonary function tests for disability appraisal including evaluation standards in chronic pulmonary disease, *Diseases of the Chest*, **24**, 378–389 (1953).

[51] R. Austrian, J. H. McClement, A. D. Renzetti, K. W. Donald, R. L. Riley, and A. Cournand, Clinical and physiologic features of some types of pulmonary diseases with impairment of alveolar-capillary diffusion, *Am. J. Med.*, **11**, 667–685 (1951).

[52] R. L. Riley, Pulmonary gas exchange, *Am. J. Med.*, **10**, 210–219 (1951).

[53] G. W. Wright and G. F. Filley, Pulmonary fibrosis and respiratory function, *Am. J. Med.*, **10**, 642 (1951).

diminishing the degree to which airways are enlarged both as to diameter and length during the inspiratory phase of respiration. There may be narrowing of the lumen of the smaller airways of a spastic[50] or permanent type such as to result in expiratory obstruction with the development of the characteristic pattern of obstructive emphysema. These abnormalities are evidenced by reduction of total lung capacity and maximum breathing capacity.

Distribution difficulty. Silicosis may interfere with even distribution of inspired air among the millions of lung alveoli by:[54]

1. Regional limitation of lung distensibility.
2. Regional obstruction of air passages either by spasm[50] or fibrosis.
3. Regional loss of elasticity.

Uneven air distribution results in overventilation of some alveoli and underventilation of others.

Silicosis may affect the distribution of venous blood among the capillaries as well as inspired air among the alveoli. This concept visualizes the distribution factor as having blood and gas components.[52–55] Uneven blood distribution results in overperfusion of some alveoli and underperfusion of others. Effective shunting of pulmonary artery blood away from diseased and improperly functioning alveoli through properly functioning ones may act as a beneficial compensatory mechanism. The importance of this phenomenon has been inadequately appreciated.[53]

Techniques suitable for analyzing the relationship of volume and speed of blood flow to alveolar size and ventilation have not as yet been fully explored.[53]

Diffusion difficulty. In addition to disturbances in the ability of the respiratory apparatus to move air into and out of the lungs, there is evidence[49,51] to suggest that in some cases of silicosis there may be interference with the direct transfer of oxygen and carbon dioxide between the blood and the alveolus. Proliferation of the connective tissue supporting the alveolar vascular bed may not only increase the distance that must be traversed by each molecule of gas but may also change the character of the medium. Under these circumstances (alveolar-capillary block), even though the pressures of oxygen and carbon dioxide (pO_2, pCO_2) in the alveoli may be normal, the venous blood brought to the alveoli will not be completely oxygenated. Since carbon dioxide passes through the altered pulmonary membrane easier than oxygen, the transfer of oxygen will be altered earlier and to a greater extent than that of carbon dioxide.[53,54] It is also important to remember that the effect of a localized diffusion difficulty may be minimized or nullified if there are enough other areas of normal functioning lung to which the blood may be shunted.[53,54]

Circulatory insufficiency. In the normal individual the pulmonary circulatory system is characterized by low pressure (29/9) and extreme distensibility. It has been shown that with the increased demands of vigorous exercise, blood flow through the lungs may be increased two and one-half to three times without any increase in normal artery pressure.[56,57] It is doubtful whether in the normal individual any increase in pressure ever occurs except under conditions of violent stress.[56] This physiologic enlargement of the pulmonary arterial tree may be interfered with in silicosis by three mechanisms: (*1*) decrease in actual size of the bed by direct obliteration of blood vessels;[53,54] (*2*) limitation of distensibility of the vascular bed by perivascular fibrosis of arterioles, capillaries, or venules;[53] and (*3*) vascular spasm secondary to local anoxia-caused ventilatory, distributory, or diffusion inadequacy, which appears to be a local anoxic effect not mediated by reflex neurological pathways.[58]

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[54] J. H. Comroe, Interpretation of commonly used pulmonary function tests, *Am. J. Med.*, **10,** 356–373 (1951).

[55] H. L. Motley, B. Gordon, L. P. Lang, and P. A. Theodos, Impairment of pulmonary function in anthracosilicosis, *Arch. Ind. Hyg. and Occupational Med.*, **1,** 133–159 (1950).

c. Clinical Approach to the Determination of Disability. The clinical approach is obviously limited. The usual disability evaluation must be undertaken in situations where malingering is a frequent factor. Reliance upon objective signs is usually obligatory, but even with this limitation, clinical observation may provide valuable information. The presence of wheezing, dyspnea, or cyanosis is significant. Exercise may elicit one or all of these symptoms, which may not be present at rest. Conversely, patients claiming inability to work may be able to walk with the examiner on the level or up a flight of stairs while carrying on normal conversation without coughing, gasping, or pausing for breath. The lack of value of such other physical findings as barrel-chest, wide costal phrenic angle, kyphosis, use of accessory muscles, impaired expansion, movement *en bloc*, hyperresonance, impaired liver dullness, impaired cardiac dullness, absent apical impulse, and impaired physical sounds in measuring pulmonary emphysema was shown by Fletcher.[59] To quote: "With regard to the clinical diagnosis of emphysema, my conclusion is that it cannot be made with any confidence (at least by a single observer) except perhaps in the most advanced cases, so that there is little hope of the clinician being able to diagnose the early stages. For this he must turn to the objective methods of the physiologist to help him in his perplexity." It must be pointed out that disability in silicosis is usually due to emphysema.

d. Roentgenology in the Study of Disability. Roentgenological studies for determination of disability in silicosis can be used in two ways: (*1*) determination of the stage of the disease and (*2*) detection of the presence or absence of emphysema. *Note:* Measurement of diaphragmatic excursion by the use of inspiratory-expiratory films appears to be of some value in determination of emphysema.[60]

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[56] J. G. Hickam and W. H. Cargill, Effect of exercise on cardiac output and pulmonary arterial pressure in normal persons and in patients with cardiovascular disease and pulmonary emphysema, *J. Clin. Invest.*, **27**, 10 (1948).

[57] R. L. Riley, A. Himmelstein, H. L. Motley, H. M. Weiner, and A. Cournand, Studies of pulmonary circulation at rest and during exercise in normal individuals and in patients with chronic pulmonary disease, *Am. J. Physiol.*, **152**, 372 (1948).

[58] G. Liljestrand, Regulation of pulmonary arterial blood pressure, *Arch. Internal Med.*, **81**, 162 (1948).

[59] J. Gough, C. M. Fletcher, J. C. Gilson, and P. D. Oldham, Discussion of diagnosis of pulmonary emphysema, *Proc. Roy. Soc. Med.*, **45**, 576–586 (1952).

Correlation of degree of lung dysfunction with extent of the disease is a matter of considerable controversy. Wright[49] feels that there is a direct correlation, "since discrete nodular silicosis is, with rare exception, entirely compatible with the working capacity adequate to determine full employment," but that "conglomerate shadows" indicate disease that is often seriously disabling. Bruce,[61] and Rossier, Bucher and Wiesinger[62] agree that only in Stage III silicosis is marked disability found. Peterson, Peterson and Startup,[63] Motley, Lang, Gordon and Theodos,[55] and Motley[50,64] present evidence to show that there is no correlation between radiologic appearance and degree of disability. It is possible to reconcile the diametrically opposed observed viewpoints by questioning the criteria for disability in the latter series. Differentiation between dysfunction as opposed to disability also is not made. The sufficiency of the allowance made for age and the degree with which some series have been weighted with disabled men are open to question. Probably the ultimate answer will await pulmonary function testing of large groups of persons of all ages exposed to silica and similar groups not exposed to silica.

e. Pulmonary Function Tests in the Evaluation of Disability. The number and variety of pulmonary function tests used during the past decade to evaluate disability in silicosis have been tremendous. It is beyond the scope of this chapter to submit a critique of the entire field of pulmonary function. The reader is referred to several excellent published studies.[49,50,54,65–67] Details of equipment and performance of individual tests can be obtained from these sources. For the present purpose, recent significant work will be summarized.

Motley,[50] in a study of 500 hard and soft coal miners with pulmonary complaints and a history of many years of exposure inside mines, concluded that:

> An accurate evaluation of the degree of pulmonary function impairment can be made from the following physiological tests: (1) Ventilation measurements from spirogram tracings (total vital capacity, three-second vital capacity, maximal breathing capacity and the shape of the exhalation curve following a deep breath), (2) the degree of bronchospasm present, (3) the residual volume and alveolar nitrogen per cent after seven minutes of oxygen breathing, (4) the arterial blood oxygen saturation at rest and immediately after step-up exercise, (5) the

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[60] Personal investigation of O. A. Sander.

[61] T. Bruce, *Acta Med. Scand., Suppl.* **129.**

[62] Rossier, Bucher, and Wiesinger, *Visch. naturf. Ges. Zurich,* 83–92 (1947).

[63] J. N. Peterson, J. M. Peterson, and C. W. Startup, *Lancet,* **1,** 147 (1931).

[64] H. L. Motley, Clinical pulmonary physiology II, *Ind. Med. and Surg.,* **22,** 262–267 (1953).

[65] E. Baldwin, A. Cournand, and D. W. Richards, Jr., Pulmonary insufficiency; physiologic classification, clinical methods of analysis, standard values in normal subjects, *Medicine,* **27,** 243–278 (1948).

[66] J. H. Comroe, ed., *Methods in Medical Research,* Vol. II. Year Book Publishers, Chicago, 1950, p. 74.

[67] R. Harvey, M. Ferrer, D. W. Richards, and A. Cournand, Influence of chronic pulmonary disease on the heart and circulation, *Am. J. Med.,* **10,** 719–738 (1951).

oxygen uptake during step-up exercise and (6) the character and duration of dyspnea after step-up exercise.

In another study Motley[64] concludes that spirography provides a tremendous amount of information on the status of the individual's lungs. He feels that impairment of oxygen transport across the pulmonary membrane may be present in some cases with essentially normal spirographic tracings, but the percentage of this group is very low. He concludes that:

> 1. Spirogram tracings of the three-second timed vital capacity and the maximal breathing capacity have been found: (1) useful screening tests of pulmonary function to detect early lung function abnormalities even before subjective or roentgenologic changes are apparent; and (2) suitable tests for annual or pre-employment examinations to detect susceptible or poor risk individuals who may be exposed to environmental lung irritants in their work. 2. The spirograms are cheap to run, rapid in measurement (five minutes), and easy and simple to obtain for permanent records. 3. The reliability of the spirogram data has been well correlated with complete pulmonary function studies on a large series of cases with all degrees of pulmonary function impairment, and a wide spread of values has been shown between the normal and the most abnormal. 4. If the observed measurements of either the three-second timed vital capacity or the maximal breathing capacity are reduced more than 15% from the predicted, the subject should be studied and evaluated further before being allowed further exposure to environmental breathing hazards.

Motley, Gordon, Lang and Theodos,[55] in studying the impairment of pulmonary function in anthracosilicosis, stress the importance of emphysema as the disabling mechanism in this disease. They point out that as the ratio of residual air to total capacity increases, the maximum breathing capacity and the vital capacity decrease. They note sharp decrease in the oxygen saturation of arterial blood with mild exercise and feel that this is a very significant measurement in the evaluation of disability indicating a disproportion between ventilation and perfusion ratios when the consumption of oxygen is increased by work. They emphasize that respiratory gas exchange may be normal at rest and yet show significant abnormality during exercise. In approximately 30 per cent of the cases studied, residual air percentage of total lung volume was within normal range. They felt that the dysfunction present in these cases was due to poor distribution, that is, inequality between well-ventilated alveoli and perfused alveoli. There was no apparent correlation between the roentgenographic stage of silicosis and the degree of impairment of pulmonary function in many cases. They conclude that an accurate evaluation of the degree of impairment of pulmonary function requires a battery of pulmonary function tests, and they condemn the use of a single test to appraise all cases. This opinion is shared by Comroe,[54] who states, "there is no single test by which all aspects of pulmonary function can be evaluated and no magic number which serves as a sharp defined line between health and pulmonary disability."

The expression of residual capacity as a percentage of total lung capacity must be interpreted with reference to age. Greifenstein *et al.*[68] have shown that the ratio is not independent of age, there being a considerable rise in the percentage in apparently healthy subjects. Gilson and Oldham[59] showed normal males, age 55, had on the average a ratio 12 per cent greater than men age 25. They felt that this indicated changes in normal individuals that are the same as those that occur in emphysema. They also point out the difficulty of using an absolute ratio in advanced pneumoconiosis of the massive fibrotic type where the increased ratio is principally due to a fall in the vital capacity, the absolute value of the residual capacity being on the average smaller than in normal subjects. Motley,[50] using an absolute ratio of 35 or above as indicative of emphysema, feels that emphysema (defined as an RC to TC ratio of over 35) "does not appear to be any more a natural part of the aging process than is hypertension. Many individuals have persistent hypertension without complaints over a period of years while actively working, yet their blood pressure is not considered normal; and the same may be said of emphysema, because individuals may have residual volumes of 45 per cent or more of total lung volume without complaints, but this increased residual volume is abnormal and does represent emphysema in most persons."

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[68] F. E. Greifenstein, R. M. King, S. S. Latch, and J. H. Comroe, *J. Appl. Physiol.* **4**, 641 (1952).

In a study of 50 men with silicosis,[69] the degree of emphysema as expressed by the ratio of residual capacity to total capacity was found to vary without any obvious correlation to the stage of silicosis. The maximum breathing capacity also showed no significant difference between the three stages of silicosis, mean values being 57 liters for Stage I; 50 for Stage II; and 45 for Stage III. Pelnar[70] proposed the use of ventilatory equivalents for oxygen and carbon dioxide simultaneously determined during rest, exercise, and recovery as a basis for disability evaluation in silicosis. This work is predicated upon the principle that people with pulmonary or circulatory disease are unable to utilize inspired air properly even at rest. During exercise, they are able to improve the utilization of air only poorly or not at all. Motley,[55] using the technique of Pelnar on 100 miners, found no correlation between ventilatory equivalents and over-all impairment of pulmonary function.

It is apparent from the above review of current work that determination of disability in silicosis through the use of function tests is not a simple matter. No single test is adequate and the problem of the significance of minimal functional aberrations remains unanswered. It is also apparent that the area of normal has never been clearly defined. One must deal not with a razor's edge, but with a saddle-back. The normal man is a nonexistent, statistical composite derived from the study of many differing individuals.[49] For example, the normal man can be expected to vary from his predicted normal by as much as 35 per cent. Thus a person whose maximal breathing capacity is 35 per cent below the predicted normal for his age must still be considered normal.[49] A 32 per cent difference in a man's maximal breathing capacity can be caused by type of equipment used in measurement.

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[69] J. Frost and J. Georg, The clinical evaluation of disability in silicosis, *Acta Med. Scand.*, **147,** 349–357 (1953).

[70] P. Pelnar, Impairment of pulmonary function in anthracosilicosis, *Arch. Ind. Hyg. and Occupational Med.*, **6,** 532 (1952).

[71] A. L. Cochrane, C. M. Fletcher, J. C. Gilson, and P. Hugh-Jones, The role of periodic examination in the prevention of coalworkers' pneumoconiosis, *Brit. J. Ind. Med.*, **8,** 53–61 (1951).

Correlation between physiological findings and anatomical findings is far from perfect in advanced stages of disability and virtually nonexistent for minor degrees of dysfunction.[49] Commonly, measurements of pulmonary function in a disabled individual indicate what the patient has left – not what he has lost. It would be more revealing and more valuable to follow progressive loss, but the opportunity to study an individual from a state of normal to a state of disease is rare. For example, a young man with a predicted maximal breathing capacity of 135 liters per minute who actually delivers 125 liters per minute would be within normal limits. Yet such is the variation of normals that his previous level may actually have been 170 liters per minute. In that case 125 liters per minute would represent a significant loss of function.

Unfortunately, most simple pulmonary function tests demand a high degree of patient co-operation. In the field of disability evaluation, where frank malingering or varying degrees of psychological aberration are common, the lack of volition becomes an extremely important obstacle.

Differentiation between impairment of pulmonary function and disability as defined by statute is of crucial importance. Minor degrees of dysfunction certainly do not represent disability. By analogy, many men who show functional circulatory abnormality, such as high blood pressure, are not disabled. The point of differentiation between impairment of function and true disability is extremely difficult to fix. The degree of dysfunction beyond which all individuals are disabled has never been established. In practice, the examiner is on certain ground only when he can show large deviations from normal.

Finally, clinicians must be cautioned not to expect too much from pulmonary function tests. Pulmonary function tests will not tell where the lesion is, what the lesion is, or even that a lesion exists if it does not interfere with the function of the lung.[54] What, then, is the role of pulmonary function testing in disability evaluation? Certainly by the use of a battery of tests a more objective appraisal of pulmonary dysfunction can be obtained than by any other means.[49,50,51,55,59,64,71] Some patients have minimal dysfunction with advanced x-ray changes and others advanced dysfunction with minimal x-ray changes.[49,50,55,59,64] Aside from aid in estimating loss that has occurred by the time of examination, serial testing year after year can give invaluable objective guidance in progression of dysfunction. It is conceivable that with the use of serial tests in some of the hazardous dusty occupations, men could be moved in time to prevent dysfunction from progressing to disability.[54,71]

What pulmonary function tests are desirable? What tests are indispensable? A priori, the popular clamor for one, single, all-embracing pulmonary function test cannot be granted. Since respiration involves a number of processes, such as total ventilation, alveolar ventilation, distribution, and diffusion, it is obvious that complete evaluation of pulmonary function will entail tests for each of the components. From a practical standpoint, factors of importance in choosing pulmonary function tests are cost, simplicity, and accuracy. Determination of diffusion gradients,[52] for example, while highly desirable, is beyond the scope of all but a few research laboratories. Fortunately, there are a number of tests, which can be performed with a reasonable degree of skill and a minimal degree of expense, that will give a sufficiently accurate result to be of help in the determination of disability. Such tests are: maximal breathing capacity, vital capacity, three-second vital capacity, determination of degree of bronchospasm, blood arterial oxygen saturation at rest and following exercise. These tests have been correlated with complete pulmonary function studies and will reveal dysfunction of sufficient severity to constitute disability.[49,50,54,55,64,69]

f. Summary. The problem of disability evaluation in silicosis is a difficult one. There are obvious moral and legal implications with opportunity for doing harm either to employer or to employee. Clinical studies and roentgenographic studies are usually of value in situations where disability is so obvious as to constitute no problem. In the borderline areas, clinical and roentgenographic evidence is often valueless or, what is worse, misleading. Pulmonary function tests are of great value, but they, too, have definite limitations. They can, however, provide the most objective and most nearly complete appraisal of pulmonary disability. They can detect significant abnormalities where clinical and roentgenographic studies fail. Used as screening measures, they can instrument removal of men from hazardous environments before dysfunction progresses to disability. Finally, complete evaluation should include use of clinical studies, x-ray studies, and pulmonary function studies correlated by a skilled, experienced examiner.

8. Control of Silicosis in Industry

a. Engineering Control. The fundamental basis for silicosis prevention is engineering control. Enclosed processes, exhaust ventilation, wet methods, and other engineering techniques can be used to insure safe concentrations of dust in the air breathed by workmen. Engineering control of dusts is discussed in Chapters IX and X.

Personal protective equipment such as filter respirators and air-line or supplied-air respirators (see Chapter XI), will under some circumstances afford protection, but such devices are poor substitutes for air sufficiently free of dust to prevent the development of pneumoconioses.

b. Medical Control. All employees with potential exposure to dangerous concentrations of free silica should be given annual medical examinations. These should include x-ray films of good quality, competently interpreted; clinical examinations; laboratory examinations in cases where it is necessary to determine infection or concomitant disease, such as cardiocirculatory dysfunction; and pulmonary function tests. When there is a question of tuberculous infection, the patient should be examined with sufficient frequency and detail to determine the exact status of the disease.

The type of routine x-ray examination used will be a major factor in determining the cost of the program to the medical department. Most roentgenologists feel that the standard 14 × 17-inch film is necessary for definite diagnosis. However, as a screening procedure, several less expensive films are available. Paper film is sometimes substituted for ordinary transparent film. Roentgenograms of this type usually show too little detail to be satisfactory even as a screening process. Roentgenograms of the 35-mm., or 4 × 5-inch, size also show insufficient detail to be dependable in the dusty trades and are not recommended by the author. Only 14 × 17-inch films of the very best quality technically should be insisted upon for the periodic observation of employees in the dusty trades. Stereoscopic and lateral films are not necessary as a routine, but may be very useful at times when a differential diagnosis becomes necessary.

The decision as to whether or not a workman should continue at his trade (either on a new job or for his old employer) is a serious responsibility of the examining physician. He not only must have a thorough understanding of working conditions in the particular occupation and plant of the worker under consideration, but also an appreciation of public health and moral responsibility to the individual worker, to his associates, and to the employer.

It unfortunately is true that most physicians who have had little experience with such matters tend to think first of separating a worker from his job, and usually so advise him. Instead of preventing disability, such ill-considered advice frequently leads to marked shortness of breath based on fear. Unless a worker has active tuberculosis, he should be kept at his regular jobs and every effort made to reduce his dust intake to a minimum. He should be assured that his lung changes will not progress to a dangerous stage with the improved dust control. In the author's experience,[72] fear caused by well-meant but exaggerated advice has caused more disability than the lung lesion itself. To many workers, an unexplained diagnosis of silicosis or asbestosis is just as serious as is a diagnosis of cancer. Far more workers will be saved from a state of semi-invalidism by reassurance and optimism than will be benefited by pessimism and too early removal from their jobs.

e. Aluminum Prophylaxis and Therapy. The use of aluminum for the prevention of silicosis was first reported by Denny, Robson, and Irwin[73] in 1937. At about the same time similar investigations were undertaken by Gardner and his associates. Since that time considerable attention has been focused on aluminum and its compounds both in laboratories and in clinics.

Tabershaw and Tebbens[74] summarized the principles that have evolved from laboratory work on both finely divided metallic aluminum and amorphous hydrated alumina as follows: If alumina and silica localize in the same phagocytic cell the effect of the silica is neutralized. Further progression of the tissue reaction characteristically produced by silica is then arrested. Mature silicotic nodules become static, and immature lesions (inflammatory and early fibrous changes) are resolved. Aluminum may remain in the tissue and protect the individual for a long period—over a year. Aluminum does not ordinarily produce toxic effects in the tissues, although it appears to increase the susceptibility of experimental animals to tuberculosis when large doses are given.

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[72] O. A. Sander, Rehabilitation of persons with pulmonary dust diseases. *Arch. Ind. Hyg and Occupational Med.*, **4**, 541–548 (December, 1951).

[73] J. J. Denny, W. D. Robson, and D. A. Irwin, *Can. Med. Assoc. J.*, **37**, 1 (1937); **40**, 213 (1939).

[74] I. R. Tabershaw and B. D. Tebbens, *J. Ind. Med.*, **14**, 709 (1945).

An occasional allergy to aluminum has been reported,[75] but this is apparently a rare occurrence. Denny, Robson, and Irwin have preferred to use metallic aluminum, but Gardner has found that certain hydrated aluminas are more satisfactory. McIntyre Research Limited, the United States agency created for licensing the use of aluminum by physicians for therapeutic or prophylactic purposes, makes only metallic aluminum available. Some investigators, notably Hannon,[76] have reported marked success in the treatment of patients with severe disability. However, when purely objective criteria have been used to measure disability, the results have been somewhat less striking. For example, in a controlled experiment by Berry,[77] 9 out of 35 silicotics were treated only with inhalations of room air, but they thought they were getting the same inhalations of aluminum dust as were the other 26 silicotics. All of the 35 had similar degrees of silicosis and similar symptoms referable to it. An impressive degree of subjective improvement was reported by the majority of the individuals in both groups and no objective improvement was noted in any of the 26 who had inhaled aluminum. This study illustrates the tremendous psychological effect of therapy and the need for controlled studies before any conclusions can be drawn on symptomatic improvement with any form of therapy.

In view of the controversial aspects of both the prophylactic and therapeutic use of aluminum in silicosis, the Council on Industrial Health[78] of the American Medical Association issued the following statement in 1946:

> The dissemination of reports on the effects of aluminum powder in the prevention and treatment of silicosis has aroused widespread interest and a demand for an authoritative statement regarding its value. At the present time the following statement would seem to be warranted; it is subject, however, to such modification as future knowledge and experience may indicate.
>
> 1. In experimental animals the prophylactic use of aluminum inhibits the toxic action of relatively pure quartz.
>
> 2. In man, industrial dust exposures often involve mixtures of various minerals in addition to quartz and other environmental variables to which experimental animals are not subject. Therefore, human silicosis usually develops more slowly and is often modified in type. Only prolonged unbiased observation, with adequate control cases, will demonstrate whether the prophylactic results obtained with animals are applicable to man.

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[75] L. H. Cotter, *J. Ind. Hyg. Toxicol.,* **26,** 7 (1944).

[76] J. W. G. Hannon, *Trans. Can. Inst. Mining Met.,* **48,** 180 (1944).

[77] J. W. Berry, Aluminum therapy in silicosis, *Am. Rev. Tuber.,* **57,** 557–573 (June, 1948).

[78] Council on Industrial Health, Aluminum in the prevention and treatment of silicosis, *J. Am. Med. Assoc.,* **130,** 1223 (April 27, 1946).

> 3. Animal experiments have demonstrated that administration of high concentrations of amorphous hydrated alumina unfavorably influences resistance to tuberculosis. While this result has not yet been reported for metallic aluminum, caution in the application of all aluminum therapy to human beings is recommended.
>
> 4. The use of aluminum might appear as an easy short-cut to healthful working conditions, thus saving large expenditures for ventilation and other control methods. Actually there is no substitute for the accepted methods of dust control.
>
> 5. If industry indiscriminately treats all employees with aluminum dust, there may be aggravation of tuberculosis or other pulmonary conditions.
>
> 6. The therapeutic use of aluminum in man appears to relieve symptoms in a very small number of cases in which silicosis develops rapidly. Experience in some groups is more favorable than in others.
>
> 7. In view of these considerations it is recommended that the general application of aluminum therapy in industry be delayed until adequately and impartially controlled clinical observation demonstrates its effectiveness in preventing or alleviating silicosis in man. In the meantime, there should be no slackening in the control measures that have been found effective in reducing the incidence of dust diseases in industry.

This statement still represents the thinking of most authorities in this country. There have been no conclusive data from scientifically controlled studies in the past ten years that make it necessary to change this statement in any way.

d. Other Therapy. In the past few years, there has been increasing interest in hormone imbalance as a cause of excessive fibrotic response and in the use of hormones to retard the progression of silicotic fibrosis in the lungs. Cortisone, insulin, estrogens, and thyroxine were shown by Schiller[79] to have an inhibitory effect on fibrous tissue production; while androgens, such as desoxycorticosterone acetate and testosterone propionate, increased the formation of fibrous tissue. Vyskočil[80] agrees that silica certainly is the primary agent that produces silicosis, but he theorizes that it does so by way of hormones and their effect on the lymphoid tissue and plasmocytes. Short- and long-term stresses tend to deplete the levels of antifibrotic hormones, resulting in increasing fibrosis. He lists tuberculous inflammation, physical fatigue, excessively hot environment, and inhalation of large quantities of dust as examples of such stresses.

Regarding the prevention of silicosis, Vyskočil concludes that it is necessary to look for a constitutional factor in persons tending to develop increased fibrotic response after inhaling silica. He feels that eventually such persons might be identified by comprehensive studies and excluded from the dusty type of work. As for treatment, he believes that silicosis already well under way can be retarded by giving ACTH and cortisone in small doses, alternating insulin with the ACTH. He further says:

> Persons with thyrotrophic evidence should be given thyroglobin, which affects experimental silicosis beneficially. Testosterone, although administered to persons having silicosis and

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[79] E. Schiller. The influence of hormones on the development of silicotic nodules, *Brit. J. Ind. Med.*, **10**, 1–8 (January, 1953).

[80] Jiří Vyskočil. Endocrine functions in silicotics. *Arch. Ind. Hyg. and Occupational Med.*, **9**, 402–413 (May, 1954).

tuberculosis by Raule and Grisler,[81] should be given, in my opinion, only to persons with active tuberculosis. It should not be given in cases of purely silicotic reactions because of the danger of enhancing the silicotic process. Important is the prevention of inflammation, both the inflammation of bronchitis in the spring and autumn and that of tuberculous origin. I suggest the prophylactic administration of salicylates in spring and autumn, as these depress the inflammatory reaction, and, as is the case with fibrous rheumatic nodules, may also beneficially affect the silicotic nodules.

Undoubtedly, we shall see much research in this direction in the next few years, which may lead to satisfactory drug prophylaxis and therapy of silicosis. The evidence today, however, is not sufficiently conclusive to warrant applying any of these methods clinically.

Until more specific therapy is available, treatment of disabling silicosis will continue to be symptomatic. It is principally directed at the associated emphysema to improve drainage of retained bronchial secretions. Bronchodilator drugs, such as Neo-Synephrine (1.5 cc. of 0.5 per cent) or Isuprel (6 to 8 drops of 1:200 solution), when placed in a nebulizer with 100 per cent oxygen and inhaled with the intermittent positive-pressure technique proposed by Motley, have given very effective results. The resulting improved ventilation, although temporary, has caused such a frank improvement in the morale and feeling of well-being of many coal miners that this form of therapy is recommended for disabling silicosis and emphysema from any cause. Courses of treatments may have to be repeated at rather frequent intervals, depending on the severity of the case.

Other measures that must be a part of the therapy regimen are prevention and active treatment of colds and other respiratory infections, the maximum possible prevention of contacts with active cases of tuberculosis, and discouragement of smoking to reduce bronchial irritation and secretion to a minimum. Any measures that will prevent bronchial obstruction are indicated. The cough reflex, therefore, should not be subdued and codeine should be withheld unless the cough is severe. Maintenance of the general nutrition of the patient also must be part of the treatment program. Continuing graded exercise is especially necessary to prevent further atelectatic areas of the lungs from developing. Support of the lower abdomen with its resulting support of the diaphragm will improve ventilation in many cases with advanced nonobstructive emphysema, but is contraindicated where there is considerable bronchial obstruction.

B. ASBESTOSIS

Asbestos is a hydrated magnesium silicate. More than 90 per cent of the raw mineral used in this country and Great Britian is produced in the Canadian chrysotile mines. Asbestos is used in two general types of manufacturing processes. It may be used either by itself or mixed with other insulating materials, such as diatomaceous earth, for fireproofing, packing, or insulating; or it may be combined with cotton and woven as a textile for fireproof and heat-resistant clothing and other substances. Lanza[82] estimates that there are about 10,000 persons exposed to asbestos in the United States. Most observers feel that the incidence of asbestosis in American asbestos workers is quite low. Asbestosis has, however, been reported more frequently in England and Canada.

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[81] A. Raule and R. Grisler, Primi risultati clinici ottenuti nella silico-tuberculosi, *Med. lavoro,* **43,** 4 (1952).

Lanza, McConnell, and Fehnel[83] concluded from their study of asbestosis that prolonged exposure to asbestos dust causes pulmonary fibrosis different from that produced in silicosis and demonstrable by roentgenogram. Clinically it resembles silicosis in that it is not disabling in the early stages, but it may be markedly disabling when advanced, and frequently leads to death by right heart failure. Although tuberculosis has been shown to be no more prevalent in persons with asbestosis than in the general population, lung cancer is under suspicion as occurring more frequently with asbestosis, especially in England.

Symptoms. The onset of symptoms of asbestosis, as of silicosis, is slow although symptoms in advanced cases are apt to be somewhat more marked than in silicosis. As in silicosis, dyspnea is the cardinal symptom. Anorexia occurs frequently in advanced stages, and cyanosis and clubbing of the fingers are apt to appear with greater constancy in asbestosis.

Pathology. The fibrosis in asbestosis is diffuse and tends to predominate in the basal portions of the lungs in contrast to the generalized nodular fibrosis of silicosis with a predominance in the upper portions of the lung. Bronchiectasis and bronchiolectasis are frequent, especially in the more fibrous portions. Whereas the proliferation of fibrous tissue is caused by chemical action in silica exposure, it is induced by mechanical action in asbestos exposures. Gardner[84] found that the fibrosis-producing character of asbestos could be almost eliminated by grinding the fibers so that no particles more than 20 μ in length were present. As previously mentioned, asbestos is classified among the inert dusts. Vorwald, Durkan and Pratt[85] report that the typical bronchiolar fibrosis is best produced by fibers ranging from 20 to 50 μ in length but not by fibers shorter than 20 μ. The significance of this finding on prevention of the disease will be discussed below.

Microscopic anatomy. Johnstone[86] described the microscopic appearance of the lungs somewhat as follows: In the early phases of the disease there is thickening of the alveolar septa which results from fibroblastic proliferation. The alveolar spaces contain numerous phagocytes. With progression of the disease fibrosis becomes more marked; the alveolar structure gradually disappears, and in its place there is now dense fibrous tissue. The few alveoli that remain in the area of fibrosis are lined with low cuboidal epithelium giving them an almost glandular appearance.

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[82] A. J. Lanza, *J. Am. Med. Assoc.*, **106**, 368 (1936).

[83] A. J. Lanza, W. J. McConnell, and J. W. Fehnel, *U. S. Pub. Health Repts.*, **50**, 1 (1935).

[84] L. U. Gardner, *Ind. Med.*, **9**, 15 (1940).

[85] A. J. Vorwald, Experimental studies of asbestosis, *Arch. Ind. Hyg. and Occupational Med.*, **3**, 1 (1951).

[86] R. T. Johnstone, *Occupational Diseases*, Saunders, Philadelphia, 1942

Scattered throughout the lung in both the diseased and healthy parts are spindle-shaped structures described first by McDonald.[87] These bodies are 20 to 100 μ in length and are bulbous on one or both ends so that they appear club- or dumbbell-shaped. They are brownish in color, do not stain, and give a Prussian-blue reaction for iron. Simson[88] has produced these bodies in guinea pigs by experimental exposure to atmosphere containing asbestos. Lynch[89] concludes that these "curious bodies" signify exposure to asbestos dust but do not necessarily indicate asbestosis. In other words, they are more properly referred to as "asbestos bodies" and not "asbestosis bodies."

X-ray examination. For an excellent review of roentgenographic findings in both silicosis and asbestosis the reader might well refer to Pendergrass.[90] Characteristic differences in the roentgenographic findings in silicosis and asbestosis are tabulated below:

Asbestosis	Silicosis
Fibrosis diffuse (film may have ground glass appearance from pleural involvement).	Fibrosis nodular.
Findings may be either bilateral or unilateral.	Findings characteristically bilateral.
Lesions largely in the lower one half or two thirds of the lung fields.	Lesions predominantly in the upper two-thirds of the lung fields.
Emphysema in upper portion of lung fields.	Emphysema in lower portion of lung fields.
Borderline degree difficult to recognize.	Borderline degree more easily recognized.

Control. Prevention of asbestosis depends largely on preventing exposure to sufficiently high concentrations of long fibers to produce the characteristic reaction. Also, if only long fibers cause the disease, fine dust respirators are not necessary. The more comfortable gauze respirators appear to be perfectly adequate filters for the long fibers. Up to this time, however, they have not been approved by the United States Bureau of Mines for this purpose.

Allowable concentrations. Dreessen, DallaValle, Edwards, Miller, and Sayers[91] have found evidence to indicate that 5 million particles per cubic foot of air is a satisfactory figure for the maximum permissible atmospheric concentration of asbestos to which workers may be exposed. However, in setting up this figure, only fibers less than 10 μ in length were counted and the longer ones were disregarded. It now appears that the shorter fibers may have to be disregarded and permissible concentrations of long fibers established, which has not been done.

The prognosis with early to moderately advanced asbestosis is good, provided the inhalation of asbestos fibers is materially decreased. Unlike silicosis, asbestosis does not tend to progress after exposure is stopped or markedly reduced. Advanced asbestosis usually is associated with considerable emphysema and commonly leads to right heart strain and failure.

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[87] S. McDonald, *Brit. Med. J.*, **2,** 1025 (1927).

[88] F. W. Simson, *Brit. Med. J.*, **1,** 885 (1928).

[89] K. M. Lynch, *J. Am. Med. Assoc.*, **109,** 1947 (1936).

[90] E. P. Pendergrass, "Roentgen-Ray Diagnosis in Silicosis and Asbestosis," in A. J. Lanza, ed., *Silicosis and Asbestosis.* Oxford Univ. Press, New York, 1938.

[91] W. C. Dreessen, J. M. DallaValle, T. I. Edwards, J. W. Miller, and R. R. Sayers, *U. S. Pub. Health Bull.* No. **241,** 1938.

C. BAUXITE PNEUMOCONIOSIS (SHAVER'S DISEASE)

A new occupational fibrosis of the lungs was recognized for the first time in 1942 by Dr. Cecil G. Shaver,[92] Niagara Peninsula Sanatorium, St. Catherines, Ontario. It is essentially a diffuse interstitial fibrosis and marked associated emphysema, with a complete absence of any nodular fibrosis. It has been found only in workers exposed to the fumes resulting from the fusion of bauxite in the manufacture of artificial aluminum abrasives.

Bauxite is a natural hydrated aluminum oxide (Al_2O_3) containing small amounts of silica and iron. When it is fused by heating at a high temperature in open electric furnaces, a crystalline artificial corundum results. This process gives off dense white fumes containing from 40 to 60 per cent aluminum and 30 to 45 per cent amorphous silica. Particle size ranges of the fume are remarkably small—from 0.5 μ down to .02 μ—and can be visualized only with the electron microscope. Workers with the heaviest exposures have been the overhead crane operators and those who shovel the mix into the furnaces.

In the early stages there are no symptoms or clinical signs. The early x-ray pattern is characterized by indefinite granular or lacelike shadows, particularly in the upper lobes, resembling early tuberculous infiltration. As the pathological changes progress, involvement of the lower lobes occurs. The shadows may remain granular or may assume an irregular nodular pattern. The root shadows usually are enlarged and increased in density. Emphysema usually is present and may be extreme, with large emphysematous blebs. Spontaneous pneumothorax has occurred in numerous cases and resulted in the death of several of these workers. The main symptom of those with advanced disease is shortness of breath. This may be sudden and extreme at the time the pneumothorax occurs. Most cases have developed in a rather short period of exposure: from two to five years.

Approximately 50 cases had been discovered in the Niagara Falls area up to about five years ago. No tuberculosis was found in any of them. Since better fume control measures have been instituted, no new cases have come to light. It is of interest that no cases of the disease were recognized until 1942, even though the fusion process had been used since 1914. The only explanation for this is the tremendous increase in production of the artificial abrasives during the war years.

The precise causative factor in the fume has not been positively identified. Heretofore, aluminum and amorphous silica had been thought to be innocuous. Also, extremely fine particles of any dust, less than 0.5 μ in size, had been thought to have no significance in the development of lung fibrosis. It was believed that such fine particles were not retained in the lungs. However, Hatch[93] has calculated that alveolar retention of particles below 0.5 μ is as great as of larger particles, and may even be greater below 0.1 μ because of Brownian motion. If this is true, then the fineness of the particles alone is an adequate explanation for the rapidity of development of this disease. Whether the silica particles alone or the aluminum particles alone are responsible, or whether the combination is necessary, has not been determined. German investigators, particularly Goralewski,[94] believed that aluminum alone was the offender and they still speak of the disease as Aluminosis. Opinion in this country, however, favors the silica fume as the toxic agent, probably modified by the aluminum particles. This seems the most logical explanation for the fact that the fibrosis does not assume a nodular character.

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[92] C. G. Shaver and A. R. Riddell, Lung changes associated with the manufacture of alumina abrasives, *J. Ind. Hyg. Toxicol.*, **29**, 145 (1947).

Interest in this disease extends well beyond the artificial abrasive industry because of the implications associated with the rapid development of fibrosis due to ultramicroscopic particles, which are harmless when larger. Is it possible that other innocuous materials may be harmful in the fume size ranges? This possibility seems unlikely for iron because of the experience with welding fumes, which contain upwards of 95 per cent iron oxide particles in size ranges below 0.1 μ and in Brownian motion. The evidence is clear, at least for this fume, that no such reaction has occurred, even in welders who had such concentrated exposures that the iron collections in their lungs could be seen by x-ray. Such exposures caused not even a trace of fibrosis in the lungs. This evidence suggests that it is not the submicroscopic particle per se that is the toxic factor in Shaver's disease. More extensive research with the fumes of many materials is needed before this interesting problem can be resolved.

D. DIATOMACEOUS EARTH PNEUMOCONIOSIS (DIATOMITE SILICOSIS; DIATOMITE PNEUMOCONIOSIS)

The first epidemiological study in the diatomite processing industry in California was reported by Legge and Rosencrantz[95] in 1932. Of 118 employees who were x-rayed, 68.5 per cent were said to have shown evidence of pneumoconiosis. No correlations were made between the degree of dust exposure and the clinical findings. There were no other American reports for the next 20 years, but a major study in Italy was reported by Vigliani and Mottura[96] in 1948. For the first time, it was shown by way of x-ray diffraction that crude diatomaceous earth contained no crystalline form of free silica, but that after flux calcining at

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[93] T. F. Hatch, J. H. Brown, K. M. Cook, and F. G. Ney, Influence of particle size upon the retention of particulate matter in the human lung, *Am. J. Pub. Health,* **40,** 450 (1950).

[94] G. Goralewski, Aluminum lung, *Arch. Gewerbepathol. Gewerbehyg.,* **11,** 102–116 (1941).

[95] R. T. Legge and E. Rosencrantz, Observations and studies on silicosis by diatomaceous silica, *Am. J. Pub. Health,* **22,** 1055–1060 (1932).

[96] E. E. Vigliani and G. Mottura, Diatomaceous earth silicosis, *Brit. J. Ind. Med.,* **5,** 148–160 (1948).

1,250° C. an intensive cristobalite pattern appeared. As had been well known for many years, cristobalite is considerably more fibrogenic than quartz. These findings appeared to account for the mild changes found in workers exposed only to the crude dust, as compared with the "malignant silicosis" shown by the workers exposed to the calcined material.

In 1952 Smart and Anderson[97] published their first report of a number of years of observation of nearly 300 diatomite workers from five plants in California, Nevada, and Oregon. They concluded that inhalation of crude diatomite dust caused only a benign linear fibrosis with no symptoms or disability. However, they found extensive, and often rapidly progressive, fibrosis following excessive exposure to calcined and flux-calcined diatomite. Occasional cases showed massive fibrotic lesions, bullous emphysema, pleurisy, cor pulmonale, and spontaneous pneumothorax. Tuberculosis was uncommon and could not be identified in any of the massive fibrotic cases. In occasional cases where tuberculosis was found, it ran a benign course until cavities developed, following which the course was downhill and therapy ineffective. Fresh-water diatomite was found less toxic than the salt-water deposits.

It should be noted that diatomite deposits are skeletal remains of microscopic aquatic single-celled plants. The shells of these plants are pure opaline silica. When the plant dies, the organic material of the cell decomposes and leaves the skeletal remains as high-grade amorphous silica. These deposits may reach a depth of several hundred feet and date back millions of years. In this country commercially important deposits are found mainly in California, Nevada, Oregon, and Washington. The material is removed by the open quarry method, with heavy-duty shovels, and transported to the mills. Its industrial uses are extensive, being a part of over 200 processes, including industrial filters, insulation materials, abrasives and polishes, building materials, insecticides, and explosives.

It has long been recognized that more factual information was needed concerning this disease before safe limits of dustiness could be established. The United States Public Health Service, therefore, was asked to make a survey of the diatomite industry on the West Coast two years ago. The report has only recently been released.[98] Five plants participated in the study.

Environmental studies were made in each of the five plants. Both salt-water and fresh-water diatomite in the crude state showed approximately 86 per cent total silica by weight. The quartz content in both crude and milled diatomite averaged 2 per cent. Cristobalite, however, was not found in the crude diatomite, but was high in the calcined and flux-calcined material. It averaged 32 per cent in the flux-calcined air-borne baghouse product. For the straight calcined product, the cristobalite was slightly less, averaging 22 per cent in the baghouse product and 17 per cent in the main product. A considerable disparity is found in the per cent of cristobalite in the parent material, settled dust, and air-borne dust, yet the total cristobalite content averaged above 20 per cent.

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[97] R. H. Smart and W. M. Anderson, Pneumoconiosis due to diatomaceous earth, *Ind. Med. and Surg.*, **21**, 509–518 (1952).

[98] W. C. Cooper, L. J. Cralley, *et al.*, Pneumoconiosis in the diatomite industry, *U. S. Pub. Health Bull.* (in preparation).

The particle size distribution ranged between 0.5 and 2.2 μ and was remarkably uniform for all types of diatomite processing. Electron microscopy showed no evidence of any predominance of low-range submicron air-borne particles. The average median dust concentrations of all operations ranged from 1 to 66 million particles per cubic foot of air, with one third of the counts being below 5 million particles, one third from 6 to 11 million particles, and one third over 11 million particles. Weighted dust exposure data were not given because it is realized that dust control at the time of the survey was far better than in the past. This is well illustrated when counts made in 1953 are compared with those made in 1954, the latter averaging less than half of the former. Modernized handling methods are replacing hand loading, which has been the dustiest of all of the operations, particularly of the straight calcined and flux-calcined products. Paper bags have replaced burlap bags, and constant attention now is being given to good housekeeping. Dust now is being trapped at the source of its generation in so far as is possible. A respirator program is in force for protection during peak loads of dustiness.

In the medical studies, 869 workers from five plants were x-rayed and 786 had complete medical examinations and laboratory studies. Tuberculin, histoplasmin, and coccidioidin skin tests were done routinely. Lung function studies also were made.

Because pathological studies had shown the importance of considering the linear pattern on the chest films with this disease and because the panel of experts agreed that it was impossible to differentiate the linear from the finely nodular in many cases, a new classification was devised. The linear and nodular changes are grouped together as LN1, 2, and 3 and the classification is set up as follows:

0 — Normal.

LN1 — Questionable linear-nodular changes.

LN2 — Definitively abnormal linear changes or nodular changes, or both, involving an area less than the equivalent of two quadrants of the lung field.

LN3 — Linear changes, nodular changes, or both, involving more than one half of the total lung area, or extending to or nearly to the periphery of both lung fields bilaterally.

C1 — Confluent shadows of uncertain or ambiguous significance, superimposed on any of the foregoing.

C2 — Massive confluent opacities definitely present, extending over less than the equivalent of three anterior rib spaces on either side.

C3 — Massive confluent opacities definitely present, extending over the equivalent of three or more anterior rib spaces on either side.

C4 — Massive confluent opacities, associated with gross distortion of the pulmonary anatomy.

Using this classification, the panel of expert chest film readers agreed on the following findings:

1. Nine per cent of 869 diatomite workers showed changes consistent with a diagnosis of pneumoconiosis, while 9.3 per cent had chest films with doubtful changes.

2. When individuals with previous dust exposures or missing occupational histories were excluded from the positive and doubtful groups, presumptive diagnoses of diatomite pneumoconiosis were made on 8.3 per cent of the employees examined, and diagnoses of borderline or doubtful stages on 6.9 per cent.

3. Of 286 employees with experience of five years or over in the diatomite industry, 22 per cent were diagnosed as positive.

4. The prevalence of abnormal chest films was particularly high in employees who had worked for over five years in the mills, about half of whom had a positive diagnosis.

5. Exposures in the quarries were less hazardous, only one of 25 employees with more than five years of exposure had a pneumoconiosis diagnosis. No quarry employees showed confluent changes.

6. Symptoms of respiratory distress or dysfunction correlated poorly with the x-ray changes, except with confluent lesions.

7. Workers with massive confluent lesions showed reduced pulmonary ventilatory function, but those with only linear or nodular changes showed no consistent pattern of disturbed function by these tests.

8. No evidence was obtained to indicate that tuberculosis, histoplasmosis, or coccidioidomycosis are related to either the linear-nodular or confluent lung changes in employees studied. Clinically active tuberculosis was not found in any workers with confluent x-ray changes. It should be noted that Smart and Anderson[97] had found nine active cases in these groups several years earlier, but these were not limited to the confluent cases.

In regard to environmental control, it was agreed after all data had been correlated that the maximal allowable concentration for crude or amorphous diatomite could safely be placed at 20 million particles per cubic foot, but that atmospheric concentrations for cristobalite-containing dust should be kept under 5 million particles per cubic foot of air. It was recommended that preplacement and periodic medical observations continue, including chest x-ray films and lung function studies.

In the writer's opinion, this was one of the most complete and conclusive occupational disease surveys made by the United States Public Health Service thus far. The suggested x-ray classification is an unusually realistic one and warrants study for its possible application to other dust diseases of the lungs.

E. COAL WORKERS' PNEUMOCONIOSIS (ANTHRACOSILICOSIS; ANTHRACOSIS)

The lung changes associated with coal mining vary markedly owing to the great differences in amount of quartz dust to which coal miners are exposed along

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[98] Anthracosilicosis among hard coal miners. *U. S. Pub. Health Bull.* No. **221**, 1935.

with the coal dust. At one extreme are the advanced cases of anthracosilicosis of the hard coal miners who have had high-grade quartz-dust exposure.[99] At the other extreme are the minimal micronodular x-ray changes in coal trimmers (ship loaders) attributed to pure coal-dust exposure (less than 1 per cent silica).[100] Practically all hard or anthracite coal lies between quartz veins, as does some soft or bituminous coal also. Most soft coal mines also have had another source of silica-dust exposure: the sand used on the rails to improve the traction of the mine locomotives. In general, it may be stated, however, that soft coal miners have had considerably less free silica exposure than have hard coal miners and many have very little, especially the sorters and loaders who do not work underground.

In the past, coal dust itself generally was thought to be innocuous. As a matter of fact, it was considered by many to have beneficial properties, in that it tended to prevent tuberculosis. However, after World War I, the increasing use of chest x-ray films revealed roentgen abnormalities in the South Wales soft coal miners that in many cases differed from the characteristic silicosis pattern. The term "reticulation" began to be used for the fine lacelike pattern seen in so many miners and trimmers. Compensation for silicosis in coal miners, under the Workmen's Compensation Act, was first granted in Britain in 1931. During World War II there was a tremendous increase in cases certified for compensation, particularly since the Act was revised in 1943 to include a disabling form of pneumoconiosis, which was not recognizable as silicosis.

In 1938 the Industrial Pulmonary Committee of the Medical Research Council began its investigations in South Wales to determine the nature of the lung disease found in coal miners. An x-ray survey was carried out in sixteen mines by Hart and Aslett,[101] and pulmonary changes were found that resembled silicosis by x-ray, but differed from it in many ways. It was recognized from this study that many coal miners had advanced and disabling disease, and that a serious hazard existed, especially in the anthracite mines, but to some extent also in the bituminous mines. A special Pneumoconiosis Research Unit was set up in 1945 in Cardiff to make more detailed studies of the epidemiology of the disease and to try to find "safe dust levels" to which men may be exposed without developing serious pneumoconiosis.

It was realized early by Fletcher[102] and his staff at the Unit that there was little agreement on methods of x-ray classification of the pneumoconioses, and that little progress toward a better understanding of the dust diseases could be expected until a system of classification was devised that would be acceptable internationally. Such a classification was set up and has been widely accepted in Europe. It was proposed to the International Conference on Pneumoconiosis in Sydney, Australia, in 1950 and accepted with minor changes. It has not been widely adopted in this country so far, but the author has noted its increasing use.

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[100] J. Gough, Pneumoconiosis of coal workers in Wales, *Occupational Med.*, **4,** 86–97 (1947).

[101] P. A. Hart and E. A. Aslett, Chronic pulmonary disease in South Wales coal miners: I. Medical studies: B. Medical survey, *Special Rept. Series* **243,** Med. Research Council, London, H. M. S. O., 1942.

[102] C. M. Fletcher, Classification of roentgenograms in pneumoconiosis, *Arch. Ind. Hyg. and Occupational Med.*, **11,** 17 (1955).

The classification has two major divisions, the simple pneumoconiosis and the complicated (see Figure 13). In the simple group, three categories are recognized, based on extent of distribution of small round opacities. The previously used term "reticulation" was dropped because it was realized that the lacelike appearance actually was due to collections of pinhead shadows.

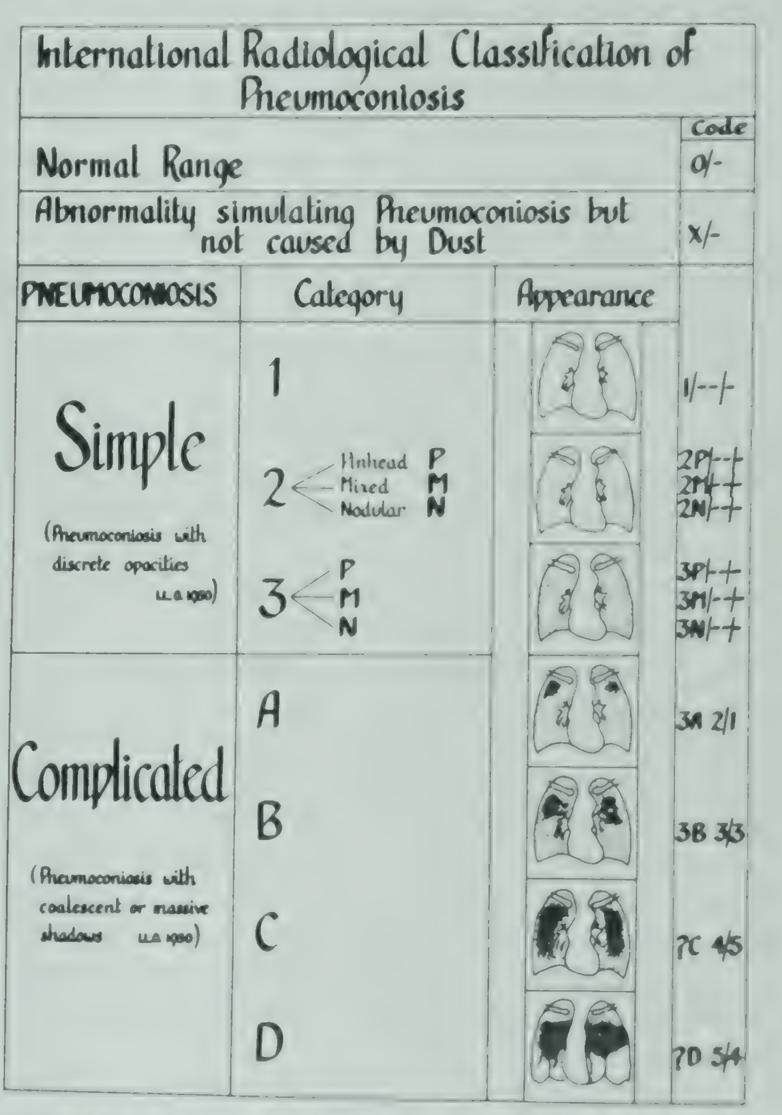
International Radiological Classification of Pneumoconiosis
Code
Normal Range
0/-
Abnormality simulating Pneumoconiosis but not caused by Dust
x/-
PNEUMOCONIOSIS
Category
Appearance
Simple
(Pneumoconiosis with discrete opacities u.a. 1950)
1
1/--/-
2
Pinhead P
Mixed M
Nodular N
2P/--/-
2M/-+
2N/-+
3
P
M
N
3P/-+
3M/-+
3N/-+
Complicated
(Pneumoconiosis with coalescent or massive shadows u.a. 1950)
A
3A 2/1
B
3B 3/3
C
?C 4/5
D
?D 5/4

Figure 13. Diagram of new international roentgenological classification of pneumoconiosis.

Categories of Simple Pneumoconiosis

Category 1. A few characteristic opacities 0.5 to 3 mm. in diameter are seen usually in the second, third, and fourth anterior rib spaces, midway between the mediastinum and periphery, more commonly on the right than on the left. Occasionally they appear more peripherally. The vascular markings are clearly visible. To make a diagnosis of Category 1 simple pneumoconiosis, the characteristic abnormality must be found in at least two rib spaces, and in each must extend over 1 sq. cm. or more.

Category 2. Opacities 0.5 to 3 mm. in diameter are more numerous and are distributed throughout the lung fields, but they are usually less profuse and are commonly absent in the peripheral third. The vascular markings are still visible although not so clearly as in Category 1.

Category 3. The opacities are now profusely distributed throughout the whole of both lung fields, including the periphery, but at the apices they may be relatively sparse.

The distinction among the categories is made chiefly on the profusion of the opacities, but their diffusion throughout the lung field, especially at the peripheral parts, and the degree of obscuration of the lung markings also are taken into account. In cases where the distribution of the opacities is uneven, the category is determined by the half lung field that shows the greatest abnormality.

Categories 1, 2, and 3 may be further subdivided into the following:

a. Pinhead type. This occurs in about 10 per cent of cases. Opacities up to 1.5 mm. in diameter are uniformly distributed throughout both lung fields, giving rise to a profuse and uniform granularity.

b. Mixed type. In these films, opacities of various sizes ranging up to 3 mm. in diameter are distributed throughout the lung fields.

c. Nodular type. In these films, discrete, more or less circular opacities, seldom more than 5 mm. in diameter, of homogeneous density are distributed throughout the lung fields. This is the usual appearance of classical silicosis.

Complicated pneumoconiosis. The earliest roentgenographic evidence of progressive massive fibrosis is the presence, on a background of Category 2 or Category 3 simple pneumoconiosis, of larger (1 cm. or more in diameter), less well-defined opacities than those characteristic of simple pneumoconiosis itself. These opacities often resemble reinfection-type tuberculosis, both in their position and in their appearance. They most commonly develop in the posterolateral segment of the upper lobes and the apical segments of the lower lobes, more commonly on the right than on the left; but the shadows are not strictly segmental, and in a posteroanterior film the commonest distribution is over a longitudinal section of the upper and mid-zones midway between the hilus and the periphery.

In the course of time, these shadows tend to grow and coalesce to form larger shadows of various shapes and sizes. New areas of opacity may develop in other parts of the lung, and ultimately a large portion of both lung fields may be occupied by massive shadows. Later, the shadows tend to contract with an increase in their density, with subsequent severe distortion of the lung architecture and with the development of gross emphysema.

The classification of these shadows is based upon the observation of the progression of the disease. They use four categories, the first three of which are distinguished chiefly on the basis of the size and extent of the shadow and the last of which indicates the presence of thoracic distortion and emphysema.

Categories of Complicated Pneumoconiosis

Category A. Shadows occupying at least one anterior rib space, generally formed by the coalescence of more or less circular shadows, more than 1 cm. in diameter, with indefinite margins and of uneven density.

Category B. Dense shadows, which are more extensive, better defined, and of more homogeneous density than Category A, but which extend over less than three anterior rib spaces.

Category C. The same type of shadow as in Category B, extending over more than three anterior rib spaces.

Category D. One of the preceding classes of shadows associated with serious distortion of the pulmonary architecture.

In the early stages of progressive massive fibrosis, the background of simple pneumoconiosis always can be seen, but as the shadows grow in extent, and particularly as emphysema develops, the underlying simple pneumoconiosis may become completely obscured. Such cases are rare, however, the vast majority still showing evidence of nodulation even after emphysema occurs.

The validity of Category 1 has been questioned in this country because pinhead shadows can be seen in the chest films of many persons who never have had dust exposure in industry. It has appeared to many that this was the stage that the late Dr. Homer Sampson liked to call the "Stage of Imagination." Fletcher, has justified it with controlled studies using seven film readers who had had wide experience in this field. He emphasizes that persons so classified never are disabled. It should be noted also that the Silicosis Board of England does not accept applications for compensation of miners having only a Category 1 classification.

Gough[100] and Heppleston have shown that the pinhead shadows are due to focal collections of coal pigment in the peribronchiolar lymphatics, referred to as coal macules. The mixed type appears to be due to a combination of coal macules and small silicotic nodules, while the nodular type usually is due to definite nodular silicosis. In the complicated groups, the confluent shadows are due to progressive massive fibrosis, which is thought to be the result of the combined effects of the tubercle bacillus and the coal dust. Fletcher thinks of coal dust as modifying tuberculous infection to the extent that many miners would have died of tuberculosis had they not had coal-dust exposure. It is noteworthy that the tuberculosis mortality always has been lower among coal miners than among all occupied and retired men in Britain. The theory that all progressive massive fibrosis in coal miners is a modified tuberculosis is strongly supported by the evidence, but is unproved.

Gough and Heppleston[103,104] also have shown that a focal type of emphysema was a characteristic finding in coal workers' lungs. At first this emphysema was thought to be due to a dilatation of the alveoli immediately adjacent to the coal macules. More detailed recent studies suggest, however, that it is essentially a dilation of the respiratory bronchioles and that the alveoli are relatively normal. The pathogenesis of the bronchiolar dilation is thought to be a direct effect of the coal deposits on the smooth muscle in the walls of the bronchioles. When such dilation becomes extensive, increase in the dead air space is thought to impair the ventilatory capacity of the lungs to the extent where exertion produces dyspnea.

This concept of disabling emphysema is in sharp contrast to that which has been generally accepted in this country. Most disabling emphysema is thought to be due to obstruction of the bronchial and bronchiolar airways. Lung function tests and the beneficial effect of bronchodilator aersol therapy by Motley[105] and others strongly suggest that airway obstruction is the principal cause of chronic diffuse emphysema. It appears likely that even though there may be a significant degree of focal emphysema in a simple pneumoconiosis case, there must still be chronic bronchial obstruction to produce breathlessness. As a matter of fact, both Fletcher and Hugh-Jones have repeatedly stated that miners with simple pneumoconiosis have little or no measurable impairment of lung function when the age factor is taken into consideration, but workers with progressive massive fibrosis may be severely disabled. Death rates from all causes among x-rayed miners in Wales showed that cases of simple pneumoconiosis have the same mortality rate as all men in England and Wales, while there is an increased mortality rate in those with massive fibrosis. This strongly suggests that focal emphysema alone is not a factor in causing right heart strain. Present evidence from the British studies, therefore, seems to indicate that simple coal pneumoconiosis and focal emphysema are not physiologically significant unless markedly advanced. Workers with minimal coal-dust deposits and disabling emphysema may have two separate entities which are unrelated, and other causes for the emphysema must be looked for.

In this country there never has been an industry-wide survey in bituminous mines, except for the study in a Utah mine by the United States Public Health Service in 1941.[106] This showed a low incidence of anthracosilicosis (3.2 per cent) and tuberculosis, and no evidence of any significant degree of emphysema. The only other American studies have been made on miners who think they have dis-

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[103] A. G. Heppleston, The pathological anatomy of simple pneumokoniosis in coal workers, *J. Pathol. Bacteriol.*, **66**, 235–246 (1953).

[104] A. G. Heppleston, The pathogenesis of simple pneumokoniosis in coal workers, *J. Pathol. Bacteriol.*, **67**, 51–63 (1954).

[105] H. L. Motley, L. P. Lang, and B. Gordon, Use of intermittent positive pressure breathing combined with nebulization in pulmonary disease, *Am. J. Med.*, **5**, 853–856 (1948).

[106] R. H. Flinn, H. E. Seifert, H. P. Brinton, *et al.*, Soft coal miners' health and working environment, *U. S. Pub. Health Bull.* No. **270**, 1941.

abling dust disease, or on those who have known disease. Quite obviously, no conclusions on epidemiology are possible with such selected groups. The vast numbers of miners with x-ray changes who remain at work without chest symptoms never are seen at all. The British Unit study in South Wales has been the only extensive unbiased survey among soft-coal miners in the world. All miners were included there, those working without symptoms as well as those with disability. Until we can have such a survey in the United States, many questions regarding coal workers' pneumoconiosis must remain unanswered.

One such question is extremely important, but unanswerable today. That is: Is there actually more disabling emphysema in soft coal miners at the various age levels than in the general population? There are numerous investigators who believe there is much more, but they lack statistical evidence to back it up. As a matter of fact, there is little factual evidence on the incidence of disabling emphysema in the general population at the various age levels. There is some evidence to suggest that this has been increasing rather rapidly in the last decade due to increased excessive cigarette smoking. Yet, there are those who would call every case of disabling emphysema in a soft coal miner an occupational disease.

Until more complete epidemiological studies of this condition are available, it seems sounder to apply a more conservative attitude in the medical control in this industry. Those with simple x-ray changes due to coal-dust deposits should be encouraged to continue their regular jobs if the dust exposure is reasonably well controlled, and not be led to believe that they are suffering from a serious disease. It has been the author's[72] experience that exaggerated opinion and advice on the dust diseases in general have frightened more workers into real respiratory disability than have the diseases per se.

Workers with complicated changes must be studied for active tuberculosis and, if none is found, must be so placed that their future dust exposure is far less than it was before. As a matter of fact, continuing efforts to further reduce coal-dust dissemination in our mines are an essential part of the over-all control of this disease. Doctors cannot be expected to encourage miners with simple x-ray changes to stay on jobs that still involve extreme degrees of dust exposure.

The matter of "what is a safe dust level?" with coal dust has not been definitely established. The Utah mine study by the United States Public Health Service suggested that 20 million particles per cubic foot might not produce serious lung damage in a working lifetime. Although levels of dustiness are not available, the author has seen many coal miners from southern Illinois coal mines, which are very wet, with no evidence of even minimal x-ray changes after 25 and 30 years of work. The British investigators also found that workers from wet mines have very little evidence of pneumoconiosis. Detailed environmental data are not yet available from the British studies. The most recent United States report on this disease, by Martin,[107] says only that "there is no good evidence as to just what dust levels are tolerable without producing significant pneumoconiosis."

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[107] J. E. Martin, Coal miners' pneumoconiosis, *Am. J. Pub. Health* **44**, 581–591 (1954).

Until that has been established, it would appear essential to examine and x-ray the chests of all coal miners yearly, as is being done with the South Wales miners. To the author's knowledge, not one coal mine in the United States is making any pre-employment or periodic chest films, which is deplorable. Mines with inadequate dust control are not being found until the miners have developed disabling disease. The coal-mining industry in the United States is alone among our dusty trades in this lack of medical control. The tremendous preventive program being carried on by the iron mines of northern Michigan and Wisconsin is a leading example of what adequate medical control can accomplish. Silicosis is becoming nonexistent except in the older miners who began mining before the dust-control measures were started twenty years ago. Prevention of any dust disease can never be satisfactorily accomplished without the periodic observation of those exposed. It is hoped that the United States coal-mining industry, including both management and labor, will soon realize this and take active steps to establish proper preventive programs where such appear to be needed.

CHAPTER XIII

Air Pollution

GEORGE D. CLAYTON

Air pollution is one of the foremost problems in public health today. People living in industrial areas are asking themselves, "Are we next?"—for episodes similar to those that occurred in Donora (Pennsylvania), the Meuse Valley, and London. An expression of this concern is the amount of newspaper space devoted to air pollution. Boddy[1] states: "One press clipping service has measured 55,000 column inches of newspaper space devoted exclusively to the Los Angeles smog situation during 1949, '50, and '51. In addition, approximately 6,500 column inches of space has been devoted to editorial comment on the problem." These figures apply only to the Los Angeles area, and can be multiplied several times over for the United States as a whole. This aroused public interest raises the question as to the origin and date of the first concern regarding the effects of air pollution.

I. History

The history of air pollution is the history of fuel, of increased industrialization, and of growing urban populations. An early prophetic clue of things to come was given in 361 B.C., when Theophrastus noted that "fossil substance called 'coals' burn for a long time, but the smell is troublesome and disagreeable." By 65 B.C., the poet Horace was lamenting that the shrines of Rome were blackened by smoke. In 1273, the first smoke abatement law was passed in England by Edward I. This law was passed because of the fears of the people that the air pollutants were detrimental to health. During this period it was believed that food cooked over burning coals would cause illness and even death. In 1306 the people became so concerned that a Royal Proclamation was signed, prohibiting the burning of coal in London. Because an owner of an industry was caught disobeying this Royal Proclamation, he was tried, found guilty, and subsequently beheaded. This is the first recorded penalty given as a result of violating an air-pollution code.

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[1] M. Boddy, Pollution and the public, *Proc. Natl. Air Pollution Symposium, 2nd Symposium, Pasadena, Calif., 1952.*

II. Effects of Air Pollution

A. ACUTE EFFECTS ON PEOPLE

The effect of air pollution upon health has been of concern to the populace since its inchoation. As mentioned above, the first air-pollution law was passed in an attempt to curb air pollutants because of their detrimental health effects. Since that time four major occurrences have justified those fears. The four major recorded air-pollution disasters are: (*1*) Meuse Valley, Belgium, 1930; (*2*) Donora, Pennsylvania, 1948; (*3*) Poza Rica, Mexico, 1950; and (*4*) London, England, 1952. These dates reveal that the disasters are becoming increasingly frequent, which is probably due in part to the ever-increasing size of our urban areas.

Meuse Valley.[2] The first well-known air-pollution disaster occurred between Seraning and Hug, in the Meuse Valley, Belgium. During the period December 1–5, 1930, a large number of persons were taken ill, and more than 60 died. Older persons with previously known disease of the heart or lungs accounted for the majority of the fatalities. The signs and symptoms were primarily those caused by a respiratory irritant. They included chest pain, cough, shortness of breath, and irritation of the mucous membranes and of the eyes. The area of the Meuse Valley where the episode occurred is approximately 15 miles long, and $1^1/_2$ miles wide and is surrounded by hills 330 feet high. Within this area there were, at the time of the disaster, the following types of industries:

1. Four very large steel plants, each having coking installations, blast furnaces, rolling mills, welding furnaces, boilers, and other operations compatible with large steel plants.
2. Three large metallurgical works.
3. Four electric power generating plants.
4. Six glass works, ceramic plants, or brick works, which were equipped with coal or producer-gas heating furnaces.
5. Three groups of lime kilns.
6. Three zinc plants, each equipped with reduction furnaces, retort drying ovens, and other operations compatible with zinc plants.
7. One coking plant (other than those associated with steel plants).
8. One sulfuric acid plant with roasting ovens.
9. One concentrated fertilizer plant, with concentration and drying ovens.

In addition to these industries discharging pollutants into the atmosphere, most of the homes and communities burned coal, thus adding considerably to the pollution load. Other sources of pollution at the time of the episode were railroads and automobiles.

The investigators considered the sources of pollution and drew up the following list of substances that could have been, and probably were, present in the atmosphere at the time of the disaster:

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[2] *Meuse Valley Air Pollution.* Royal Academy of Medicine of Belgium, December 19, 1931, pp. 683–732.

hydrogen
sulfur dioxide
sulfur trioxide (sulfuric acid)
hydrochloric acid
hydrofluoric acid and its salts, ammonium fluoride and zinc fluoride
carbon monoxide
carbon dioxide
hydrosulfuric acid
nitric oxide
nitrogen dioxide (NO_2)
nitrous acid (HNO_2)
nitric acid (HNO_3)
ammonia and ammonium salts (thiocyanates, sulfides)
ammonium sulfide
saturated and unsaturated hydrocarbons, including natural gas and gasoline vapors
odor of organic products (not identified) from phosphate plants
drops of tar, phenol, naphthalene, and so forth
soot
cement dust
lime dust
metal dust
zinc oxide
lead
arsenous acid anhydride
arsine
methyl alcohol
ethyl alcohol
formaldehyde
zinc chloride
silica from Bessemer Steel Works

The meteorological investigators found the meteorological conditions for Monday, December 1 through Friday, December 5, 1930 to have been anticyclonic in nature, characterized by high atmospheric pressures and mild winds of a general easterly direction. During this period the fog became increasingly worse. There was considerable cooling during the night, often as much as 10° C. The wind was a very mild east wind, not exceeding 5 miles per hour and often dropping during the days of December 2, 3, and 4 to 1.6 miles per hour.

After the investigators had checked all the available data on the medical, meteorological, and environmental factors, efforts were made to determine the causative agent. Many of the contaminants could be eliminated immediately because their known toxicological action was not compatible with the medical findings. Other contaminants were eliminated because it was decided that the concentrations could not have been sufficient to cause the damage found. From all the findings the investigators concluded the contaminants most likely to have caused the symptoms were sulfur compounds; however, they added that the synergistic effect of the other contaminants may have played an important part.

Donora.[3] The second well-known air-pollution disaster occurred in Donora, Pennsylvania, during the period of Wednesday, October 27, to Sunday, October 31, 1948. Within this period 20 people died and 6,000 became ill.

In Donora, at the time the investigation was being conducted, there were the following industries:

1. One large steel plant having blast furnaces, looping rod mills, wire drawing department, and wire finishing department.

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[3] H. H. Schrenk, H. Heimann, G. D. Clayton, and W. N. Gafafer, Air pollution in Donora, Pennsylvania, *U. S. Pub. Health Bull.* No. **306.**

2. One zinc plant equipped with reduction furnaces, retort drying ovens, and other operations compatible with zinc plants.

3. One sulfuric acid plant.

Other heavy industries in the nearby area, which interested the investigators, included: two steel companies and one by-product plant in Monessen; a steel and by-product plant in Clairton; a glass company in Charleroi; and a power company and a railroad in Elrama.

A study of the plant processes and analyses of the raw materials used in those industries led the investigators to analyze the atmosphere for the following constituents:

Total particulate matter
Lead
Cadmium
Zinc
Iron
Chloride
Fluoride

Acid gases
Hydrogen
Arsine
Arsenic
Sulfur dioxide
Total sulfur
Carbon dioxide

Carbon monoxide
Oxygen
Oxides of nitrogen
Stibine
Manganese
Iron carbonyl

The investigators concluded that:

> It seems reasonable to state that while no *single* substance was responsible for the October, 1948, episode, the syndrome could have been produced by a combination or summation of the action of two or more of the contaminants. Sulfur dioxide and its oxidation products, together with particulate matter, are considered significant contaminants. However, the significance of the other irritants as important adjuvants to the biological effects, cannot be finally estimated on the basis of present knowledge.
>
> Information available on the toxicological effects of mixed irritant gases is meager, and data on possible enhanced action due to adsorption of gases on particulate matter is limited. Further, available toxicological information pertains mainly to adults in relatively good health. Hence, the lack of fundamental data on the physiologic effects of a mixture of gases and particulate matter, over a period of time, is a severe handicap in evaluating the effects of atmospheric pollutants on persons of all ages and in various stages of health.

Although sufficient data were not available to determine the exact causative agent, sufficient environmental data were available to make ten recommendations which, if fulfilled, would prevent a recurrence of the disaster.

Poza Rica. The third much-publicized incident occurred in Poza Rica, Mexico,[4] on November 24, 1950, with a record of 22 persons dead and 320 people hospitalized.

A review of the history of the incident shows that the sulfur-removal unit (Girbotol unit) began operation on November 21, 1950. A few days after the unit was in operation trouble developed, when the amine solution overflowed, partly plugging the gas lines to the pilot lights of the flares. However, the flare appeared normal under the reduced rate of flow.

On November 24, 1950, at approximately 2:00 A.M., efforts were made to increase the rate of flow of gas to the plant's rated capacity of 60 billion cubic feet per day. The desired rate of flow was reached at approximately 2:30 A.M. At approximately 4:00 A.M. difficulty was encountered, and the gas flow began surging through the unit, with the probable result that unburned hydrogen sulfide escaped into the atmosphere.

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[4] L. C. McCabe and G. D. Clayton, Air pollution by hydrogen sulfide in Poza Rica, Mexico, *Arch. Ind. Hyg. and Occupational Medicine*, **6**, 199-213 (1952).

The available meteorological data indicate a pronounced low-altitude temperature inversion, a high concentration of haze and nuclei, and a very slight wind movement prevailing.

The epidemiological study indicated that the time of onset of the incident was about 4:50 A.M., and the acute phase was ended about 5:10 A.M. The victims were affected in a geographical area in direct proximity to the effluent stack of the Girbotol unit. During this short period, the acute exposure to the atmospheric pollution caused the death of 22 people and the hospitalization of 320.

The onset, the symptoms and signs, as well as the pathological findings, are consistent with hydrogen sulfide poisoning, and there were no findings that conflicted with this diagnosis. Therefore, it is to be concluded that the hydrogen sulfide that caused this morbidity and mortality came from the effluent stack of the Girbotol unit.

London. During the period December 5–8, 1952, the fourth and worst air-pollution disaster occurred. When these deaths were being recorded, the London area experienced periods of smog, culminating in one of much intensity. The onset was accompanied by meteorological factors of low temperature inversion and almost complete absence of wind or air movement. No radio or balloon-sonde ascents were made within the fog belt. Ascents at Cardington, 50 miles north of London, where visibility did not fall below 1,000 yards during the period, show a continuous inversion from ground level up to heights between 500 and 1,000 feet. Reports from aircraft landing at London Airport after the fog had cleared temporarily place the height of the inversion at 200 to 300 feet, with a haze layer extending to 2,000 feet.

This is the first air-pollution disaster where air sampling was conducted before, during, and after the episode. The data collected showed the particulate matter (obtained by sampling with filter paper and reporting the degree of color in milligrams of total weight per cubic meter of air) ranged from 0.30 to 0.84 mg. per cubic meter of air, with an average of 0.50 for the two-week period preceding the disaster. On the days when deaths were occurring, the values increased to a maximum of 4.46 mg. per cubic meter of air, a ninefold increase over the previous average.

Sulfur dioxide ranged from 0.09 to 0.33 p.p.m. with an average of 0.15, for the two-week period preceding the disaster. During the period when deaths were occurring the SO_2 values increased to a maximum of 1.33 p.p.m., which was also a ninefold increase over the average of the preceding days.

During the weeks ending December 13 and December 20, 1952, at least 3,000 more deaths occurred than would be expected. Although the increase was present in every age group, the greatest increase was in the age group of 45 years and over. More than 80 per cent of these deaths occurred among individuals with known heart disease and respiratory disease. As in other disasters reported, the symptoms produced were associated with irritation of the respiratory tract.

The British Ministry of Health concluded: "The fog was, in fact, a precipitating agent operating on a susceptible group of patients whose life expectation, judging from their pre-existing diseases, must even in the absence of fog, have been short."

A study of the four disasters reveals these similarities:

1. People died, and many more became ill.
2. Each area was subject to an unusually long period of inversion.
3. Each area was subject to natural fog.
4. There was no new or unusual activity in the community prior to the disaster. Each area (except Poza Rica) had been essentially the same for many years with no unusual effect on the people.
5. The symptoms experienced were similar to those caused by a respiratory irritant.
6. Older people, and especially those with previous heart and respiratory disease (except in Poza Rica), were more severely affected than the younger age groups and normal health groups.
7. With the exception of Poza Rica, the agent or agents that caused the deaths are unknown.

It is apparent that the first step necessary to prevent more disasters is to determine the causative agent or agents. Until this is done, the exact procedures to be used to prevent such occurrences will be only "educated guesses." Until this knowledge is available, it is unreasonable to expect industry and other sources of pollution to control emissions to a level that would prevent a disaster under such a chance or freak meteorological occurrences. However, it is desirable to have a plan for each urban area that could be put into effect if a prolonged temperature inversion did exist. Such a plan could include requesting people with heart and respiratory disease to move from the affected area, and placing those who could not leave the area in an auditorium equipped with proper air-cleaning devices.

B. CHRONIC EFFECTS ON PEOPLE

The preceding section has dealt with the acute effects of air pollution. The other facet of this health problem is the chronic effects, which are more elusive. In order to ascertain these effects, answers must be found for such questions as:

1. What effect does atmospheric pollution have on persons with pre-existing maladies, such as disease of the respiratory tract, heart disease, and possibly others?
2. What effect does air pollution have on elderly people who, by the aging process, naturally develop degenerative diseases of the lungs and heart?

3. What effect does air pollution have on children, who have an increased respiratory rate, as well as increased metabolism?

4. To what extent does air pollution lower the resistance of persons so as to predispose them to infectious diseases, particularly of the respiratory tract?

5. Does air pollution have any effect on the mental health of individuals?

To answer such questions, one must know more about the properties and effects of the contaminants themselves, such as:

1. What concentration of contaminants is required to produce acute and chronic effects?

2. Does a combination of contaminants act individually, is the effect additive, or is the effect greater than the summation of the individual effects?

3. Under what meteorological conditions would contaminants increase to harmful concentrations?

These determinations must be made before one can adequately evaluate the "long-term" effects of atmospheric pollution on the health of the general population. Only general knowledge is presently available, such as the fact that atmospheric pollution does decrease the quantity of the germicidal rays of the sun, and in this way, may indirectly produce adverse effects. It is also known that irritating gases and large amounts of particulate matter present in the atmosphere may reach concentrations that would have an adverse effect. The extent of such injurious effects is not known.

The maximum allowable concentrations of many toxic substances have been established for protecting the health of employees in industrial plants. However, these concentrations have been established for an 8-hour day and for the type of personnel normally employed in industry, in relatively good health, aged 18 to 60. Hence, the maximum allowable concentrations familiar to industrial hygienists throw little light on amounts that can be breathed safely 24 hours a day, by the general population, including the very young and the aged, as well as persons with organic diseases, and those with special sensitivity to respiratory irritants.

To date, information available on the toxicological effects of mixed irritant gases is meager, and data on possible enhanced action due to sorption of gases by particulate matter are also limited. Obtaining the necessary data will require both laboratory and field work on an extensive and time-consuming scale. Although these long-range studies are essential to the solution of the problem of atmospheric pollution, this does not mean that practical control procedures cannot be carried forward in the interim. It does mean, however, that careful thought and planning are necessary if orderly progress is to be made.

There have been two attempts on the part of official agencies to determine the chronic effects of air pollution on health. First, in 1955 the California State Department of Public Health studied the Los Angeles smog and its health effects.[5]

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[5] *Clean Air for California.* California State Department of Public Health, San Francisco, Calif., March, 1955.

They concluded that:

1. There is no association between hospital admissions due to diseases of the heart and respiratory system, and the periods of air pollution in Los Angeles during the months studied.

2. Industrial absenteeism was not affected by periods of high smog.

3. The sickness survey conducted by the State Health Department did not reveal any measurable effect from the Los Angeles smog during August through November, 1954.

4. The examination of Los Angeles mortality during the months of August through November, 1954, disclosed no excessive mortality during the smog periods.

5. The infant mortality data revealed no significant relationship during periods of smog and periods of no smog.

The second investigation on the chronic effects of air pollution is being conducted in the Detroit (Michigan)-Windsor (Ontario) area. This work is a consolidation of efforts by many official agencies, including the Detroit City Health Department, United States Public Health Service, Province of Ontario Health Department, and the Canadian Department of Health. The methodology[6] included mortality and morbidity studies. The morbidity data included reportable diseases, school health records, industrial health records, hospital records, and special morbidity studies, such as sample surveys for the collection of specific sickness data. As this study is not yet completed, no results are available.

C. EFFECTS ON VEGETATION

The civic beauty of an urban community is often reflected in the upkeep of its parks and the landscaping of its homes. The farms at its outskirts are an essential part of a prosperous community. The effects of atmospheric pollution on vegetation are therefore an important consideration. A polluted atmosphere may injure plant life more than animal life. The effects of polluted air on plants may show in stunted growth, loss of vigor, reduced crop yield, and degradation of color. Sunlight is more directly essential to plants than to animals, for the plant depends on light falling on its leaves for the conversion of carbon dioxide to the carbohydrates that largely make up its substance. Light is as essential to plants as carbon dioxide. On an annual basis, the light reduction caused by pollution in the atmosphere may be up to 40 or 50 per cent. Further loss is experienced by the plant if a coating of particulate matter accumulates on its leaves making it increasingly difficult for the life-giving rays of the sun to reach the leaf and tending to choke the minute openings of the leaf through which the plant breathes. Particulate matter causes further damage to the living cells and destroys chlorophyll by holding the acid gases in the atmosphere in contact with the leaf. When chlorophyll is treated with dilute acids, a derivative called pheophytin is formed, in which the magnesium atom of the chlorophyll nucleus is quantitatively replaced by hydrogen. A stronger concentration of acid, or more prolonged treatment, degrades the chlorophyll to lower breakdown products that no longer show the characteristic spectral absorption bands of chlorophyll and pheophytin. In many cases the leaves and tender plants are scorched beyond recovery. Further increase in acidity of the soil, due to atmospheric pollution, can adversely affect vegetation.

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[6] G. D. Clayton, Epidemiologic approach, *Proc. Nat'l. Air Pollution Symposium, 2nd Symposium, Pasadena, Calif., 1952.*

Damage to vegetation was first reported in Los Angeles in 1944. The characteristic of the injury was a silver or bronze metallic sheen, or glazed appearance, on the lower leaf surface of such plants as sugar beets, swiss chard, spinach, and endive. Since 1944 the damage to plants in the Los Angeles area has become increasingly severe, and it is reported that the loss to farmers is as much as several million dollars annually.

Haagen-Smit,[7] Koritz and Went,[8] and others report that the reaction products of ozone with hydrocarbons produced plant damage similar to that caused by smog. The discovery that a filter of activated carbon would remove the agent or agents causing the plant damage indicated the pollutant was gaseous in nature rather than particulate. Went[9] reported that he found damage to vegetables and tobacco in Berkeley, California; New York City; Philadelphia, Pennsylvania; Baltimore, Maryland; and London, England. He states: "In all these cities the damage symptoms were undoubtedly produced by oxidized hydrocarbons."

The effect of sulfur dioxide on plant life is fairly well known; factors that influence it are temperature, humidity, water, and age of plants. Zimmerman[10] reported the following:

> *Susceptibility of species:* plant species varied in their susceptibility when exposed together to known concentrations of sulphur dioxide gas. Buckwheat and alfalfa are among the most sensitive plants to sulphur dioxide, being marked in seven hours by 0.4 ppm. Barley, oats, rye, sweet clover, and tomato were marked in five hours by 0.66 ppm of sulphur dioxide. Castor bean, salvia, and pepper were marked by 1.0 ppm during the course of a five-hour treatment. Turnip, lettuce, egg plant, and endive were injured in one to two hours by 1 ppm. Lily and four species of orchids not in flower were not marked with a five-hour treatment at 4.3 ppm of sulphur dioxide. This concentration severely injured the other species, listed above, when fumigated for one hour.

Hydrogen fluoride contamination has been the subject of much investigation because of the large number of lawsuits involving this pollutant. The following species of plants have consistently shown injury at 0.1 p.p.m. hydrofluoric acid gas: buckwheat, peach, apricot, prune, gladiolus, crabgrass, corn, bean, sweetpotato and pine. Table 1, prepared by Zimmerman, shows comparative susceptibility of various species.

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[7] A. J. Haagen-Smit, *et al., Plant Physiol.,* **27,** No. 1, 18–34 (1952).

[8] Koritz and F. W. Went, *Plant Physiol.,* **28,** No. 1, 50–62 (1953).

[9] F. W. Went, *Distribution of Plant Injury Due to Organic Air Pollutants.* Earhart Plant Research Lab., Calif. Inst. of Technol., 1952.

[10] P. W. Zimmerman, Impurities in the air and their influence on plant life, *Proc. Natl. Air Pollution Symposium, 1st Symposium, Pasadena, Calif., 1949.*

TABLE 1

Comparative Susceptibility of Various Species to Hydrofluoric Acid Gas[a]

Time of exposure	Concentration (av. p.p.m.)	Buckwheat	Sweet potato	Peach	Tomato	Corn	Bean	Pine
2 hr. 10 min.	1.48	4	—	4	4	4	4	4
2 hr. 10 min.	0.67	3	3	3	1	3	1	4
4 hr.	0.27	3	2	2	0	—	0	4
7 hr. 30 min.	0.135	3	3	3	0	3	0	4
4 hr.	0.13	1	1	1	0	1	0	2
6 hr. 40 min.	0.085	1	1	1	0	0	0	2
4 hr.	0.07	0	0	0	0	0	0	1

[a] Extent of injury is indicated as follows: 0, no injury; 1, slight; 2, medium; 3, considerable; 4, severe injury.

Ammonia, hydrogen sulfide, mercury vapor, ethylene, and carbon monoxide gases are also toxic to plants in relatively high concentrations. However, the number of reputed cases of injury involving these gases is not sufficient to warrant detailed discussion here.

From the foregoing, it is apparent that air pollutants in small concentrations can and do affect vegetation, that certain plants are more susceptible than others, and that each pollutant often produces a characteristic damage, which is identifiable.

These factors very often make plants ideal "instruments" for measuring air pollutants. The aluminum industry has for years planted gladioli and other plants and trees in circles as far as 10 miles from the plant, in order to assess fluoride damage. The use of indicator plants for evaluating the air pollutants prior to the construction or enlargement of a plant, where the effluent is known to be injurious to plants, is sound practice. It is especially so, if the proposed plant is in an industrial area where the effluent from other plants may already be sufficient to cause damage under unfavorable meteorological conditions. Indicator plants can be used for routine evaluation of certain air pollutants.

D. EFFECTS ON STRUCTURES

Another familiar effect of atmospheric pollution is discoloration of buildings, including stone, brick, and painted surfaces. Blackened surfaces and encrustations of sooty material frequently obliterate essential lines and decorations. They disfigure a building and seriously reduce its aesthetic and decorative value. More serious, however, is the corrosive action of acid gases on buildings. One of the effects of this reaction is the formation on stone surfaces of hard, impermeable skin that tends to blister and exfoliate. It has been reported that sheets of galvanized iron had a life span of 3 to 6 years in Pittsburgh, prior to its active air-pollution control program, as compared with 7 to 14 years in a smoke-free community; and that, at the same time, copper would last only 10 to 20 years in Pittsburgh, whereas it would be good indefinitely where there is relatively little atmospheric pollution. The effect of certain acid gases on paint is well known, as exemplified by the blackening of white lead-base paint by hydrogen sulfide.

III. Economics of Air Pollution

It is not possible to state a figure that would accurately proclaim the cost of air pollution to urban dweller, farmer, retailer, and industry. No one can deny, however, that air pollution has a serious effect on the economics of an industrial community, although the extent varies by community, and even by individual company and person. Some industries, because of their air pollution, have been ordered by the courts to close their plants or install expensive control procedures. In these cases, the economic hardship due to air pollution is almost overwhelming. A number of people suffer physically because of an allergy to some contaminant in the air, and must leave the community in order to obtain relief.

Several organizations have given "guesstimates" of the cost of damage due to air pollution in the United States. The Commerce Department estimated the cost ranged from 8 to 20 dollars per inhabitant annually. The United States Geological Survey reported that smoke damage to merchandise and buildings was 500 million dollars per year. In 1953 an economic loss of 3 million dollars on only eleven crops was attributable to smog in Los Angeles. Gibson[11] estimates the direct economic loss to the United States to be at least $1^1/_2$ billion dollars annually.

The part air pollution plays in causing the decay of certain areas of our communities, where businesses move to outlying areas of the city, is impossible to determine. It is safe to assume, however, that it is an important consideration and causes tremendous loss of tax revenue to the local government. One of the principal causes of this large economic loss is sulfur dioxide. It has been estimated[12] that the amount of sulfur compounds emitted to the atmosphere from various sources is greater than the present world production of native sulfur and pyrites combined. This raises the question as to the extent air pollutants can be recovered either to assist in amortizing the cost of installation of control equipment, or to provide a product that is a definite asset to the company. Some instances of recovery that might be cited are:

1. A large utility company achieved control of fly ash at a considerable cost; it now sells the fly ash at a substantial profit.

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[11] W. B. Gibson, *Proc. Natl. Air Pollution Symposium, 1st Symposium, Pasadena, Calif., 1949,* p. 109.

[12] M. Katz and R. J. Cole, *Ind. Eng. Chem.,* **42,** 2258 (1950).

2. The control of rare metals by a mint paid for itself in one year.

3. The sale of sulfur dioxide recovered by a Canadian smelter yielded more profit than the original product.

Whether or not there is a profit or loss in the control of air pollutants is incidental to the fact that the day is fast approaching when management must consider the control of sources of pollution as an integral part of the cost of construction and maintenance of a plant.

IV. Sources and Kinds of Air Pollution

Sources of pollution may be divided into two major classifications: *(1)* "natural" and *(2)* man-made contaminants. Three outstanding examples of natural air pollution in recent times are: the Katmai volcanic eruption, whose emissions clouded the Northern Hemisphere in 1902 and 1903; the MacKenzie forest fire of 1951, which obscured the sun across a great swath of Canada and the United States, causing street lights to be turned on at 9 A.M. in Philadelphia, Baltimore, and Cleveland; and the devastating dust storms that raged through Texas, Oklahoma, and Kansas in the 1930's, as well as the dust storms of the past few years.

TABLE 2

Estimated Emissions of Aerosols, Acid Gases, and Aldehydes to the Atmosphere, Los Angeles County

(In tons per day)

Source	Aerosols[a]	Oxides of nitrogen[b]	Sulfur dioxide	Aldehydes[c]	Organic acids[d]
Chemical, paint, roofing, rubber, soap, food, fertilizer, metal & mineral industries	61	[f]	27	[f]	[f]
Fuel oil burning[e]	3	85	170	[f]	7
Transportation, diesel	7	10	2	1	3
Transportation, gasoline	25	132	21	10	7
Petroleum refining	5	—	80	—	—
Incineration, domestic	90	21	[f]	10	55
Incineration, commercial, industrial, municipal and dumps	34	7	[f]	4	18
Total	225	255	300	25	90

[a] Includes smoke, dusts, fumes and mists.

[b] Reported as nitrogen dioxide.

[c] Reported as formaldehyde.

[d] Reported as acetic acid.

[e] Includes fuel oil burned in all categories except transportation. All values based on summer fuel oil usage, which is approximately one half of the winter usage.

[f] Less than one ton.

It has been estimated that in Detroit approximately 40 per cent of the particulate pollution would remain in the area if all human activity stopped.

The pollution of the air from man-made activities ranges from the cooking of meals at home to the effluents from large metal-smelting plants. It is unfortunate that, except in Los Angeles, little is known of the relative amounts from each of these sources. Table 2 gives an estimate of the amounts of emissions found in Los Angeles in 1951.[13]

A. POLLUTION IN VARIOUS CITIES

Sulfur dioxide is probably the most common of the contaminant gases found in the community atmosphere, being formed in the combustion of most fuels, with some coals having a very high percentage of sulfur content.[14] Certain industrial processes emit several tons of sulfur dioxide per day.[15] Henderson and Haggard[16] state that the least detectable odor of sulfur dioxide is from 3 to 5 p.p.m.; however, it may be "tasted" in much lower atmospheric concentrations.

Sulfur dioxide is of interest to air hygienists because, in sufficient concentrations, it corrodes building materials, destroys cloth and leather, and affects vegetation and human health. The economic effects of sulfur dioxide have been the subject of much discussion. In London it is reported that the sulfur gases have seriously defaced the stone and other building material, as well as statues and other ornaments used to beautify the city. Also in London, library leather-bound books deteriorate as the result of sulfur dioxide.[17]

As for the effect of sulfur dioxide on human health, there are no acceptable data at the present time that incriminate it as the responsible agent in concentrations sufficient to cause sickness resulting in death.

The effect of sulfur dioxide on plant life is much better known. Setterstrom[18] states: "Factors influencing the effect of sulfur dioxide on plants are: (1) Resistance was greater at 40° F. or below; (2) resistance decreased with increases in relative humidity; (3) ample water supply made them more susceptible; and (4) younger plants were more resistant than old ones."

The average sulfur dioxide concentrations found in various cities[10,19-21] range from 0.001 to over 0.40 p.p.m., depending on the city and the time of year. In Detroit 96 per cent of 18,000 $^1/_2$-hour readings were less than 0.15 p.p.m., and 57 per cent of these were 0.05 p.p.m. or less. Average monthly values of 0.02 p.p.m. were recorded during the summer months of June and July. During the winter months the average values reached a high of 0.11 p.p.m. in December.

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[13] Air Pollution Control Dist., Co. of Los Angeles, Calif., *Second Tech. and Admin. Rept.*, 1950/51.

[14] L. R. Burdick and J. P. Barkley, Concentration of sulphur compounds in city air, *U. S. Bur. Mines Inform. Circ.* No. **7066,** April, 1939.

[15] L. T. Fairhall, *Industrial Toxicology*. Williams and Wilkins, Baltimore, 1949.

[16] Y. Henderson and H. W. Haggard, *Noxious Gases*. 2nd ed., Reinhold, New York, 1943.

[17] Conditions of library atmosphere, *Atmos. Poll. Bull.,* **16,** No. 1 (1948).

[18] C. Setterstrom, Effects of sulfur dioxide on plants and animals, *Ind. Eng. Chem.,* **32,** 473 (1940).

[19] S. H. Richards, The measurement and survey of atmospheric pollution, *J. Roy. Sanit Inst.,* **71,** No. 3 (1951).

[20] *Atmospheric Pollution in Leicester—a Scientific Survey*. H. M. S. O., London, 1945.

[21] C. Setterstrom, Sulphur dioxide content of air at Boyce Thompson Institute, *Contribs. Boyce Thompson Inst.,* **10,** No. 2, 183–187 (1939).

Another gas found in the community atmosphere is *hydrogen sulfide,* which at ordinary temperatures has a specific gravity of 1.19 referred to air and has, in very low concentrations, a powerful characteristic odor. The sources of this gas may be a wide variety of industrial processes, including refineries, sewerage installations, oil fields, and, in slight amounts, auto exhaust. Air hygienists are interested in hydrogen sulfide because of its effects on health, its odorous characteristics, and its economic effects. The toxic effects are well known. In the field of air pollution, it was identified as the atmospheric contaminant that killed 22 people and hospitalized 320 in Poza Rica, Mexico.[4]

The economic effects of hydrogen sulfide are best illustrated by the discoloration of lead-pigmented paints, the reported incidents of which are too numerous to mention. It should be stated, however, that these reported observations occurred during times when the excess liberations of hydrogen sulfide may be classified as accidents. During normal periods the hydrogen sulfide never reaches such concentrations. Moreover, it does not damage plants in low concentrations. Zimmerman[22] states that when 29 plant species were fumigated with less than 40 p.p.m., little or no injury occurred.

Data on the concentrations of hydrogen sulfide in various cities are limited. In general, however, except for accidents, or in the direct path from a known source, the concentrations range from 0.000 to 0.020 p.p.m.

Hydrogen fluoride, with respect to air pollution, is one of the most important halogen compounds. Hydrogen fluoride is liberated into the atmosphere from many sources; however, the biggest problems to date are in areas near aluminum plants and phosphate-fertilizer plants. The petroleum industry, in the synthesis of high-octane gasoline, uses considerable amounts of anhydrous hydrogen fluoride. Tables 3 and 4 show the data reported by Largent on concentrations of fluoride and hydrogen fluoride.[23]

Fluorides are also used, and are a source of air pollution, in the electrolytic refining of metals, pickling of metals, electroplating operations, etching of glassware, steel manufacturing, and cement plants. Although coal varies[24] in fluoride content, its burning results in the emission of fluorides.

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[22] P. W. Zimmerman, "Effects on Plants of Impurities Associated with Air," *Proceedings of the U. S. Technical Conference on Air Pollution*. McGraw-Hill, New York, 1952, Ch. 13, p. 127.

[23] E. J. Largent, "Effects of Air-borne Fluorides on Livestock," *Proceedings of the U. S. Technical Conference on Air Pollution*. McGraw-Hill, New York, 1952, Ch. 6, p. 65.

[24] A. E. Crossley, Fluorine in coal: IV. The industrial significance of fluorine in coal, in steam-raising, gas-making and brewing. *J. Soc. Chem. Ind. (London)*, **63**, 34 (1944).

TABLE 3

Concentrations of Fluoride in the Atmosphere

(Within or in the vicinity of certain factories as reported by several investigators)

Location	Concentrations of F in air		Observer
	mg./m.^{3}	p.p.m. as HF	
Danish cryolite plant (inside)	16–497	18–547	Roholm
British aluminum plant (inside)	0.04–3.77	0.05–3.43[a]	Agate
British aluminum plant (outside)	0.03–0.22	0.04–0.24	Agate
U.S. rock phosphate plant (outside)	0.02–3	0.01–4.3[b]	Largent

[a] Maximum amount reported in the gaseous form was 2.79 p.p.m.

[b] Maximum amount reported in the gaseous form was 0.029 p.p.m.

TABLE 4

Fluoride Content of Samples of Air Collected on a Farm Adjacent to a Rock Phosphate Factory

	Fluoride in air expressed as HF	
1947	Gaseous component (p.p.m.)	Total, including dust (p.p.m)
June	0.012	0.012
	0.024	4.3
July	0.012	0.024
	0.024	0.056
August	Nil	Nil
	0.029	0.040
October	Nil	Nil
	—	0.173

In sufficient concentration, hydrogen fluoride is toxic to humans; however, the damage to plants and livestock from gaseous and particulate fluorides has received more attention. The gladiolus is one of the most sensitive plants, being injured in atmospheres having values of only 1 or 2 parts of fluorine to a billion parts of air. In livestock, fluorosis results in irregularly worn teeth, a stiff-legged gait, poor nutritional state, and a reduction in the output of milk.

Clayton and Giever,[25] using filter paper as the collecting medium, reported an average fluoride concentration in Detroit of 0.12 μg. per cubic meter of air; using a standard impinger, the value was 0.87 μg. per cubic meter of air. They concluded the difference between these values probably could be accounted for by the gaseous fluorides.

Oxides of nitrogen. Nitrogen dioxide and its polymer, nitrogen tetroxide, are found together in the atmosphere. Some of the sources of this gas are the manufacturing of nitric acid and the nitration of cellulose and other organic materials, as in the manufacture of celluloid and certain types of film. It is also liberated into the atmosphere during the etching of metal with aqua regia and from the combustion of fuel, especially in internal combustion engines. Oxides of nitrogen are of concern to the investigators in Los Angeles, as they are a component of the total oxidants found in that area. They may be of concern also in areas such as bus terminals, and in areas adjacent to those industrial plants where excessive amounts of nitrous fumes are emitted.

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[25] G. D. Clayton and P. M. Giever, "Report on 1951 Environmental Findings." March, 1953. United States Section, International Joint Commission, Technical Advisory Board on Air Pollution.

The West Virginia health department found a maximum concentration of 0.92 p.p.m. nitrogen oxide in Charleston, with the highest average at any one station of 0.20 p.p.m., and averages from the other five fixed sampling stations ranging to a low of 0.09 p.p.m.[26] In Los Angeles, investigators found the concentration of nitrogen dioxide on a clear day averaged 0.08 p.p.m. and on days of intense smog it increased to an average of 0.4 p.p.m.

A study of available data reveals that *ozone* is apparently a significant atmospheric pollution problem prevailing in the Los Angeles area, where a chemical analysis of the air during smog periods reveals that the most characteristic property of the atmosphere is its oxidizing capacity. Haagen-Smit[27] states that ozone formation and peroxide formation are phenomena closely related to the eye irritation and crop damage in the Los Angeles area.

Ozone, because of its powerful oxidizing action, disintegrates rubber, corrodes, metals, and damages crops. There is voluminous literature on the toxicity of ozone to humans. Stokinger has given an excellent review of the literature on the subject, and shows the conflicting information to date.[28] The effects of ozone, or total oxidants, and other pollutants on health are very well reported in the Los Angeles area. Ozone has been blamed for the eye irritation and for causing skin irritation.

The economic loss due to ozone is probably best exemplified by the damage it does to rubber. In fact, rubber is so sensitive to ozone that the concentration of ozone has been determined by the rubber cracking test.[29]

Ozone and total oxidants are present in most communities in concentrations of approximately 0.01 p.p.m. In Los Angeles, however, the concentration of total oxidants (ozone, peroxides, and nitrogen oxides) reaches levels of 0.8 p.p.m. during periods of severe smog. An odor of smog begins to occur at 0.13 p.p.m., and eye irritation is recorded at 0.25 p.p.m., according to Haagen-Smit. Smith[30] reports that the normal concentration of ozone in the Detroit area is less than 0.01 p.p.m. On several occasions, during periods of smog, concentrations as high as 0.2 p.p.m. have been recorded there.

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[26] *Atmospheric Pollution in the Great Kanawha River Valley Industrial Area, Feb. 1950–Aug. 1951.* Bureau of Industrial Hygiene, West Virginia Dept. of Health.

[27] A. J. Haagen-Smit, Formation of ozone in Los Angeles smog. *Proc. Natl. Air Pollution Symposium, 2nd Symposium, Pasadena, Calif., 1952.*

[28] H. E. Stokinger, *Ozone Toxicity—A Review of Literature through 1953.* Div. of Occupational Health, U. S. Public Health Service, Cincinnati, Ohio, November, 1953.

[29] A. J. Haagen-Smit, Smog research pays off, *Eng. and Sci.*, **15** (May, 1952).

[30] R. Smith, personal communication.

Carbon monoxide is one of the most prevalent atmospheric pollutants. Although automobile-exhaust gas is considered the primary source of carbon monoxide in city streets, there are many industrial and residential sources of this contaminant. Bloomfield's study [31] of 14 cities in 1927 found an average carbon monoxide value of 80 p.p.m. The Bureau of Sanitary Engineering of the Department of Health, City of Chicago, in 1926 found carbon monoxide as high as 36 p.p.m. in that city. Cholak,[32] in 1952, showed an average carbon monoxide concentration in Baltimore of over 10 p.p.m.; in Cincinnati commercial and industrial areas, 9.5 p.p.m., residential areas, 4.0 p.p.m.; and in Donora, Pennsylvania, 5.0 p.p.m. Castrop, Stephens, and Patty [33] found in 380 tests in Detroit a maximum of 80 p.p.m. at the 5-foot level, with a mean of 28.9 p.p.m. in heavy traffic, 12.3 in medium, and 6.9 in light traffic. A similar number of tests in Los Angeles revealed a maximum of 160 p.p.m. with means of 58, 27.5, and 11.8 in heavy, medium, and light traffic. The mean for all tests on smog-free days was 9.7, and for tests during smog, 39.4 p.p.m.

Particle fall in large cities is very much higher than in the surrounding country. The monthly average deposit of from 31.7 to 54.2 tons per square mile, has been reported [34] whereas in the surrounding country the particle fall is 11.2 tons per square mile. In Detroit the monthly mean particle fall ranged from 40.5 tons per square mile in August to 82.7 in April.

Table 5 presents data tabulated by the California State Health Department[5] showing the highest values obtained for various contaminants in some California cities.

The United States Public Health Service has been periodically sampling the atmosphere for particulate matter in certain American cities. Tables 6, 7, and 8 present a summary of their findings to date.

Careful review of the available data reveals that little information is actually available on the pollutants in urban atmospheres, and virtually nothing is known of the physical or chemical state in which the pollutants exist in the air. Until these data become known, the progress on determining the effects air pollutants have upon a community will be slow.

V. Control Procedures

There are many methods for keeping the discharge of air pollutants to a level that is unobjectionable to the community. These are: (*1*) air-cleaning devices, (*2*) dilution, (*3*) substitution, and (*4*) zoning.

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[31] J. J. Bloomfield and H. S. Isbell, The problem of automobile exhaust gas in streets and repair shops of large cities, *U. S. Pub. Health Repts., Reprint* No. **1217,** March 30, 1928.

[32] J. Cholak, The nature of atmospheric pollution in a number of industrial communities, *Proc. Natl. Air Pollution Symposium, 2nd Symposium, Pasadena, Calif., 1952.*

[33] V. J. Castrop, J. F. Stephens, and F. A. Patty, A comparison of carbon monoxide concentrations in Detroit and Los Angeles, *Am. Ind. Hyg. Assoc. Quart.,* **16,** 225 (1955).

[34] E. A. Allcut, *Eng. J. (Can.),* **30,** 154, 164 (1947).

TABLE 5

Highest Reported Values of Atmospheric Pollutants,[a] Selected California Urban Areas

Pollutant	Los Angeles	San Francisco Bay Area[b]	San Diego	Santa Clara
	(parts per million parts of air, by volume)			
Acrolein	Trace	NA	NA	—
Aldehydes	0.80	NA	0.62	0.6
Carbon monoxide (CO)	42.9	NA	3.3	1.2
Hydrocarbons (HC)	2.09	NA	1.39	NA
Hydrogen sulfide (H_2S)	NA	NA	NA	0.9
Oxidants	1.00	0.32	0.22	0.33
Nitrogen oxides (as NO_2)	1.45	NA	0.65	0.3
Sulfur oxides (as SO_2)	0.3	NA	NA	0.06
	(micrograms per cubic meter of air)			
Particulate matter				
Aluminum (Al)	8	NA	NA	NA
Arsenic (As)	0.65	0.07		0.03
Beryllium (Be)	0.002	0.0003		0.0004
Calcium (Ca)	7	NA		—
Carbon (C)	132	NA		—
Copper (Cu)	1.40	0.296		0.61
Fluoride (F^-)	65	NA		—
Iron (Fe)	18.3	5.2		6.4
Lead (Pb)	42	3.5		0.9
Magnesium (Mg)	19.6	6.0		6.9
Manganese (Mn)	1.86	0.118		0.05
Organic particulate mat.	254.0	69.5		43.6
Nitrate (NO_3^-)	116	NA		—
Potassium (K)	7.2	2.52		2.5
Polycyclic hydrocarbons	24.6	NA		—
Silicon (Si)	28	NA		—
Silver (Ag)	0.0027	<0.0008		<0.0009
Sodium (Na)	8.6	7.4		4.9
Sulfate (SO_4^{--})	154.5	25.0		4.65
Sulfuric acid	110	NA		—
Strontium (Sr)	1.08	0.16		0.05
Tin (Sn)	0.96	0.05		<0.01
Titanium (Ti)	1.02	0.21		0.24
Vanadium (V)	0.169	0.013		0.014
Zinc (Zn)	NA	0.02		0.47
Total	1220	298		400

Particulate radioactivity	San Francisco Bay Area (range, Curies per cubic centimeter)
Alpha	1×10^{-19} to 3.8×10^{-17}
Beta-gamma	1.5×10^{-18} to 2.8×10^{-16}

Source: Air Pollution Foundation; California Institute of Technology; Air Pollution Control District, County of Los Angeles; San Diego County Smog Committee; Santa Clara County Health Department; Stanford Research Institute; United States Public Health Service; Univ of California, Berkeley.

[a] Measurements for complaints not included.

[b] Excludes Santa Clara County.

NA = not available.

TABLE 6

Analyses of Particulates in Atmosphere of Various Cities

(Average values in $\mu g./m.^3$)

	Populations over 2,000,000					Populations between 500,000 and 2,000,000						
	Los Angeles	Detroit	Philadelphia	Chicago	New York	Cincinnati	Kansas City	Portland	Atlanta	Houston	San Francisco	Minneapolis
Acetone-soluble	57.3	50.9	30.0	45.8	37.7	31.4	18.4	32.1	24.2	18.5	19.4	15.8
Mn	0.15	0.74	0.54	0.11	0.07	.24	0.08	0.23	0.12	0.23	0.11	0.08
Pb	5.2	2.9	9.5	2.8	2.8	1.6	1.0	1.2	1.8	1.0	2.4	0.5
Sn	0.02	0.06	0.16	0.03	0.08	0.03	0.03	0.01	0.03	0.02	0.02	0.01
Fe	4.7	8.3	6.5	7.9	5.2	4.5	4.1	5.1	3.3	4.0	2.4	4.4
V	0.002	0.025	0.174	0.002	0.322	0.09	0.002	0.009	0.024	0.001	0.002	0.002
Cu	0.13	0.57	1.34	0.11	0.30	0.18	0.04	0.05	0.01	0.02	0.07	0.60
Be	0.0001	0.0004	0.0005	0.0002	0.0003	0.0002	0.0003	0.0003	0.0002	0.0002	0.0001	0.0002
Ti	0.30	0.28	0.15	0.18	0.41	0.06	0.21	0.24	0.12	0.29	0.04	0.11
As	0.02	0.04	0.16	0.04	0.05	0.02	0.02	0.02	<0.01	0.01	0.01	0.01
F^-	0.38	0.04	0.24	0.03	0.21	0.21	0.01	Nil	0.05	Nil	0.37	0.06
SO_4^{--}	14.4	7.5	15.6	9.4	14.8	5.6	1.5	0.8	1.0	2.4	1.8	0.8
NO_3^-	14.4	1.2	1.6	1.7	0.8	1.0	0.6	0.2	0.8	1.0	3.4	1.3
Total load	265	344	188	280	244	176	146	143	137	129	104	120

TABLE 7

Analyses of Particulates in Atmospheres of Nonurban Areas
(Average values in $\mu g./m^3$)

	Vicinity of				
	Boonsboro	Salt Lake City	Atlanta	Cincinnati	Portland
Acetone-soluble	8.7	6.2	9.3	9.0	12.6
Mn	0.00	0.04	0.11	0.07	0.04
Pb	0.1	0.1	0.9	0.4	0.3
Sn	<0.01	<0.01	<0.01	0.01	<0.01
Fe	3.7	4.1	2.7	2.4	3.6
V	0.003	Nil	0.004	<0.001	0.002
Cu	Nil	0.28	0.01	0.19	<0.01
Be	0.0001	<0.0001	0.0002	0.0001	0.0001
Ti	0.26	Nil	0.13	0.01	Nil
As	0.01	0.03	0.01	<0.01	0.04
F^-	—	—	Nil	0.26	—
SO_4^{--}	0.3	<0.01	0.5	1.9	0.4
NO_3^-	—	—	—	0.7	—
Total load	68	55	71	45	86

TABLE 8

Relationship between Averages of Total Particulates and Organic Fraction

	Average total load ($\mu g./m.^3$)	Average acetone-solubles ($\mu g./m.^3$)	Per cent acetone-solubles
Large cities			
Los Angeles	265	57.3	21.6
Philadelphia	188	30.0	15.9
Detroit	344	50.9	14.8
Chicago	280	45.8	16.4
New York	244	37.7	15.5
Intermediate cities			
Cincinnati	176	31.4	17.8
Kansas City	146	18.4	12.6
Portland	143	32.1	22.4
Atlanta	137	24.2	17.6
Houston	129	18.5	14.3
San Francisco	104	19.4	18.6
Minneapolis	120	15.8	13.2
Washington	130	27.3	21.0
"Atypical" cities			
Anchorage	308	21.4	6.9
Charleston	288	25.4	8.8
Fort Worth	110	14.1	12.8
Nonurban areas			
Boonsboro, Md.	68	8.7	12.8
Salt Lake City	55	6.2	11.3
Atlanta	71	9.3	13.1
Cincinnati	45	9.0	20.0
Portland	86	12.6	14.7

A. AIR-CLEANING DEVICES

The most effective and positive method of controlling air pollutants is at the source, with proper air-cleaning devices. This method of control is adequately discussed in Chapter IX.

B. DILUTION

The dilution or dispersion of the pollutants prior to reaching the ground level from tall stacks has been the subject of extensive study for many years. In 1932 Sutton[35] developed a theory on dispersion by assigning an expression of the appropriate dimensional form to the correlation coefficient of Sir Geoffrey Taylor's statistical theory of turbulence. Shortly thereafter Bosanquet and Pearson[36] published in the *Faraday Society Reports* a theoretical equation based on voluminous studies of smoke from stacks of different heights, which in substance is as follows: The peak concentration of an effluent reaching the ground from a stack occurs about 10 stack lengths from the base; and varies inversely as the square of the stack height. This means that the ground concentration from a 145-foot stack would be approximately 17 times that of a 600-foot stack. After the peak, the concentration falls off until after some 50 stack lengths it varies as the inverse square of the distance from the source.

The temperature of the gases being emitted also has considerable influence on the ground concentrations. The investigation of Hill, Thomas, and Abersold[37] shows clearly the effect of stack gas temperature on ground concentrations. During periods of low wind speed, the effluent rising from a stack continues to rise until it encounters air of equal density. Then it disperses laterally in all directions. The height that the effluent will reach will depend on its temperature unless it is forced out of the stack at great velocity. It is estimated that each degree Fahrenheit of rise in stack temperature is the equivalent of $2^1/_2$ feet of added stack height.

Scorer[38] has pointed out that there is a great advantage in giving the plumes the largest possible cross section, since this will minimize losses of their buoyancy to the surrounding air and so raise the height to which they will eventually rise. In his words, "The objective should be, therefore, to get them as high into the air as possible by means of a very few tall, wide chimneys and a certain amount of buoyancy."

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[35] O. G. Sutton, A theory of eddy diffusion in the atmosphere, *Proc. Roy. Soc. (London).* **A135,** 145–165 (1932).

[36] C. H. Bosanquet and J. L. Pearson, The spread of smoke and gases from chimneys, disperse systems in gases, dust, smoke and fog—a general discussion, *Trans. Faraday Soc.,* **32,** 1249–64 (April, 1936).

[37] C. R. Hill, M. S. Thomas, and J. H. Abersold, Effectiveness of high stacks in overcoming objectionable concentrations of gases at ground level, *Ind. Hyg. Foundation Amer., Proc. of Ninth Annual Meeting, November, 1944.*

[38] R. S. Scorer, Plumes from tall chimneys, *Weather,* **10,** 106–109 (1955).

The use of high stacks is successful in the West where the population is sparse. It should be used with caution, however, in heavily populated areas, as the net effect of high stacks is to disperse the pollutants over a large area at high altitudes and so may reduce sunlight, give an appearance of dirtiness to the whole area, and in general insult the aesthetic senses of the community.

Another method of control through atmospheric dilution that is receiving increasing consideration is curtailing or shutting down operations when the meteorologic factors preclude adequate dilution. One of the first such procedures used was in Trail, British Columbia. When ground concentrations reached a certain level, the plant curtailed or shut down operations until the weather conditions were more favorable for dispersion. Later this smelter employed large holding tanks and discharged their effluent into these tanks until the weather conditions were favorable, then the contents of the tanks were discharged into the atmosphere. In 1954 the Governor of California requested the oil refineries to shut down until meteorologic conditions became more favorable. Los Angeles County now has a plan whereby industry, automobiles, and other sources of pollution will cease operation if weather factors prevent dispersion for an extended period of time.

C. SUBSTITUTION

The principle of substituting materials and methods to lessen hazards has been used successfully for many years in industrial hygiene. It has been used to some degree also in air-pollution work. Probably the most noted example of this method of control is the substitution of Diesel for coal-burning engines on trains. Until this change came about, the switch engines, particularly, were a constant cause of complaint from the citizens. In addition to improving their relations with the smoke inspectors and the community, the railroads found that the Diesels were more efficient and more economical.

Many industrial processes today contributing to air pollution can be redesigned to comply with the most rigid air-pollution law if adequate deliberation is given to the problem by the process engineer in cooperation with the air-pollution engineer. Wise management takes air pollution into consideration before expanding present facilities or building new plants.

Another example of this method of control is the elimination of backyard incineration, as recommended in Los Angeles, and the substitution of other means of disposal, such as the use of sanitary landfills.

In Los Angeles one theory has been that reduction in the emission of hydrocarbons from auto exhausts would eliminate the smog problem. There have been many suggestions as to how this can be done. One method considered by the authorities is the use of an alternate fuel to gasoline, such as liquefied petroleum gases. Another possibility is the limiting of the number of automobiles in the area, providing in their place an adequate mass transit system.

London, England, has been bothered with air pollution for many years.

Several groups studying the problem have recommended that central heating systems be installed and the homes provided with heat from these systems, in order to eliminate one of the major sources of pollution, the home heating unit. The central heating units could easily be provided with proper controls for the elimination of smoke.

D. ZONING

Zoning as a method of control has merit in eliminating nuisances, but if meteorologic conditions were such as to cause a disaster in the area, this procedure would have little value, unless the plants were requested to close. In zoning a community, consideration must be given to prevailing wind direction and speed, wind turbulence, frequency and severity of temperature inversions, and topography. After these factors have been considered and the community zoned, residential buildings should be prohibited in industrial areas, as industry is prohibited in a residential zone. In applying the principle of allocating land for industrial purposes, it is desirable to know the maximum levels that various contaminants can reach before injury to health and excessive damage to property occur, so that some measures could be taken to prevent the contaminants from reaching such levels.

VI. Legislation

A. PAST PRECEDENTS

How limited is the power of the states to control air pollution? Could control be so stringent as to ruin an established business, regulate the manner of doing business and the use of property, or prohibit it altogether, or require large expenditures for equipment, if necessary? An answer to these questions can be obtained by reviewing state laws and state and federal court decisions.

The only prohibitive provisions in the federal Constitution that apply to the police power to control smoke nuisance (or air pollution) are the "due process" and "equal protection" clauses of the Fourteenth Amendment, which states: "Nor shall any state deprive any person of life, liberty, or property, without due process of law; nor deny to any person within its jurisdiction the equal protection of the law." This clause, however, has not been a strong factor in defense tactics, as it has been settled that any provision of a statute or ordinance regulating a nuisance (such as smoke) is valid, in so far as the due process clause is concerned, if it is reasonably necessary for the accomplishment of the purpose and for the public welfare generally, and if it is not unduly oppressive, does not arbitrarily interfere with private business, nor place extraordinary and needless restrictions upon a lawful occupation. The pivotal point of the cases tried has been the "reasonableness" of the law in dispute—which rests on the facts and circumstances of each case. It has been settled that a law is not invalid because it puts an establishment out of business, or requires expenditure of large sums of money to comply with terms of the law; nor because there are no appliances available to prevent the prohibited fumes or smoke.

Because the law can regulate a business to the extent of closing it, it is expedient to familiarize oneself with cases brought to test. Essentially, the earliest cases involving smoke and other pollutants of the air were tried on the "nuisance" clause where there was no specific ordinance prohibiting the action or condition that was obnoxious. One of the earliest cases settled on the "nuisance" clause was *People* v. *Detroit White Lead Works*, 82 Michigan 471, 46 N.W. 735 (1890). A large paint factory operating in the midst of a populous community was prosecuted for "consistently producing odors, smoke and soot of such noxious character, and to such an extent that they produce headache, nausea, vomiting and other pains and aches injurious to health." The corporation and its officers were convicted of violating a Detroit ordinance prohibiting any factory from allowing any nuisance on the premises within the limits of Detroit, even though the business was carried on in a careful manner and nothing was done that was not a reasonable and necessary incident to the business. The court said: ". . . whenever such a business becomes a nuisance, it must give way to the rights of the public, and the owners thereof must either devise some means to avoid the nuisance or must remove or cease the business. It may not be continued to the injury of the health of those living in its vicinity." Note that the date was 1890.

On the other hand, contrary to the above ruling, in several cases involving private nuisances the businesses involved were found not guilty of violations because the court said they were using the best-known modern appliances to prevent smoke and fumes, as in *Downs* v. *Greer Beatty Clay Co.*, 29 Ohio C.C. 328, 58 A.L.R. 1226 (1905); and *Price* v. *Carey Mfg. Co.*, 310 Pa. 557, 165 Atl. 849 (1933).

Glucose Refining Co. v. *City of Chicago*, 138 Fed. 209, 215 (1905), was settled on the basis that smoke and fumes constitute a nuisance, as was *Northwestern Laundry* v. *Des Moines*, 239 U. S. 486, 60 L ed. 396, 401 (1915), which is often quoted and used in settling other cases to this day. In its decision on the laundry case the court said, "Nor is there any valid Federal Constitutional objection in the fact that the regulation may require the discontinuance of the use of the property or subject the occupant to large expense in complying with the terms of the law or ordinance."

Many interesting questions have arisen in connection with court cases, several of which are of import to industry:

1. How much damage must be shown by the person or persons bringing suit?
2. Does "coming to the nuisance" influence a decision?
3. Where there is more than one source of pollution, must plaintiff show damage from each one specifically?

In reply to the first, actual damage need not be shown. The "reasonableness" of the ordinance is usually the deciding factor. The courts have been meticulous in adhering to the true meaning of the word "damage," having ruled against the plaintiff in a number of cases because they held that the resulting condition was not "damage" but rather an "inconvenience." It is interesting to note that in several instances in Missouri, Ohio, and Minnesota, where decisions were made in favor of the industry or business, it was only on the grounds that the city or local body bringing suit did not have the power to do so. More and more in recent years this has been changed by the "enabling legislation" enacted by the states.

With reference to question 2, generally the "right of habitation" takes precedence over the right of industry or trade. Where population growth approached a nuisance, the decisions of the courts were: ". . . it is the duty of those liable at once to put an end to it" (*Mahone* v. *Autry* [1951] 55 N. Mex. 111, 227, p. 623) and ". . . one cannot erect a nuisance upon his land adjoining vacant lands owned by another, and thus measurably control the uses to which his neighbor's land may in the future be subjected" (*City of Rochester* v. *Charlotte Docks Co.*).

With reference to question 3, instances in which one source was not responsible for enough pollution to constitute a nuisance, but the total contribution of two or more sources of pollution *was* a nuisance, were adjudged cases of joint liability. Recent rulings have held those responsible for the various contributions to be "joint tort feasors" or at least not in position to object if the court divides the damages between them as best it can. In another case (*Permanente Metals Corp.* v. *Pista*, CCA 9 [1946]) where the court found it was not possible to differentiate between the damage arising from injury attributable to the defendant, and damage which had another origin, the trier of the facts "should be left to make from the evidence the best possible estimate." In *Learned* v. *Castle*, 78 Cal. 454—". . . a wrongdoer who contributes to a damage cannot escape entirely because his proportional contribution to the result cannot be accurately measured."

B. PRESENT STATUS

An examination of the state statutes shows that all states have the requisite authority to engage in air-pollution control activities or to delegate such authority to cities or other political units if these do not already possess such power. Many local governments have the authority to implement air-pollution programs, although in some states it was first necessary to pass "enabling legislation" to strengthen and clarify the authority of the local governments. In California, Kentucky, New Jersey, Pennsylvania, and Wisconsin either some or all counties have been authorized to conduct air-pollution control programs. New York has given the authority to towns (townships).

The study of the past and present legislative data reveals the trend for larger and larger areas to be under one air-pollution control authority. Many state legislative bodies have submitted bills designed to create state-wide air-pollution control programs; to date very few such bills have become law. Los

Angeles in 1947 initiated the trend in the direction of larger control areas. There the control district is composed of some 30 different communities, and the idea is now expressed by many that the present Los Angeles control district is too small to be effective and should be enlarged to include an area known as the Los Angeles basin. Another example of the trend toward larger control areas is Oregon where, in 1951, a state law was passed establishing a statewide air-pollution program. Pennsylvania, in 1949, was one of the first states to initiate a state-wide surveillance of air pollution. This law states, in part: "General legislation operating uniformly throughout the state is necessary. . . ."

In New Jersey an air-pollution law has been enacted on a state-wide basis. In this law air pollution is defined as ". . . the presence in the outdoor atmosphere of substances in quantities which are injurious to human, plant or animal life, or to property throughout the state and in such territories of the State as shall be affected thereby, and excludes all aspects of employer-employee relationship as to health and safety hazards."

The latest example of this trend is in California where it is recommended in the booklet *Clean Air for California* (prepared by the California Department of Health) in part, that the state ". . . recognize air pollution in all its facets as a matter of state concern, with its health aspects paramount."

VII. Meteorology and Topography

A. IMPORTANCE IN PLANT LOCATION

In determining the location of a new plant, consideration should be given to the climatology of the area. Important elements of the climate of the region are the temperature and precipitation. Temperature is considered with respect to its annual mean, its annual march, and its daily range. Precipitation is considered with respect to its annual mean, its annual march, its variability, and its distribution between rain and snow. Of equal importance are the velocity and direction of the prevailing winds, the humidity, degree of cloudiness, and frequency and severity of inversions.

Three main factors determine the climate of a given locality: (*1*) general atmospheric circulation, (*2*) latitude, and (*3*) physiographic nature of the terrain. In analyzing wind records, it must be understood that the average annual patterns may give a false sense of security, especially if the proposed plant is in a valley or enclosed partially by hills. Recent wind-tunnel tests have indicated that the height and shapes of surrounding buildings have an important effect on wind patterns. Therefore these factors also must be taken into consideration in the design of a plant.

Before and after construction of a plant, a competent industrial hygienist or air-pollution engineer should be employed to make periodic tests to determine if the collecting devices are operating efficiently, to observe the effects of the pollutants on the surrounding neighborhood, to maintain proper public relations with the control officials in the area, and to maintain proper public relations with the community.

B. EFFECT ON AIR POLLUTANTS

The role of meteorology in air pollution is based on the diffusion mechanism. Elaborate diffusion equations have been developed for idealized conditions of single sources of constant shape, location, and strength. Although these equations cannot be used directly in the complex problem posed by the large industrial area, they indicate generally which meteorological factors are important in the dispersal of contaminants in the air.

These equations indicate that the concentration of pollution is inversely related to the mean surface wind speed and directly related to the stability of the atmosphere. To elaborate, the greater the lapse rate, the more vigorous is the turbulence; the more vigorous the turbulence, the more rapid the diffusion. Hence, high pollution is associated with small lapse rates (that is, stable air), and low pollution with large lapse rates (that is, unstable air).

Some other features of the influence of meteorology upon air pollution that are not so directly related to diffusion are: influence of changing wind direction, the synoptic weather situations characteristic of high pollution and low pollution, the effect of cold frontal passages, and the influence of rainfall.

The degree of concentration or dilution of contaminants depends on the amount dispersed and on meteorologic factors, particularly turbulence, wind speed, and direction. Turbulence is dependent on the vertical temperature variation, temperature lapse rate, as well as the wind speed and the terrain of the ground and surface structures. Atmospheric stability for an extended period of time (4–5 days) has been characteristic of each of the recorded air-pollution disasters. Under these meteorologic conditions the atmospheric contaminants increase in concentration. In Los Angeles the highest concentrations of air contaminants are to be found during periods of low temperature inversion and low wind speed.

The turbulence or diffusivity of the air undergoes daily cyclic variations. During the daylight hours, and particularly around mid-afternoon, when winds, on the average, are strongest and temperatures decrease rapidly with height, the ability of the air to accept and effectively diffuse pollution is at a maximum. This cycle is so pronounced that the results are evident to all in the form of early morning smog over most cities. In general, industry's pattern of activities makes good use of the daily variation in the diffusivity of the air, but techniques of delayed emissions or rescheduling of operations might harness this cycle even more effectively.

In most parts of the country, with clear skies and average daytime wind speeds, a nighttime temperature inversion will develop, culminating in relatively stagnant air and an increase of pollution. Usually a few hours of sunlight will suffice to "burn off" the inversion and decrease the pollution. However, there are times when unusual atmospheric conditions produce an inversion of such intensity that it persists throughout the day, on into the next night, or perhaps for several days. During such periods, air pollution disasters have occurred, and in Los Angeles the people have been subjected to eye irritation and the other discomforts of smog.

Because of the key role played by the inversion, it is worthy of more detailed consideration. It has been stated that the presence of turbulence is vital to the diffusion of air pollution. Recent research has demonstrated that an inversion damps out the turbulence, leaving laminar air-flow conditions or, in extreme cases, completely calm conditions.

VIII. Practical Considerations for Plant Management

Aggressive management today considers air-pollution problems as fundamental as the availability of water, manpower, and electricity. The control of air pollution is expensive. There are very few bargain basement solutions to the problem. However, there are usually several satisfactory methods of controlling the situation, and those companies who employ industrial hygienists or air-pollution engineers are fortunate, as these people can often save the organization considerable sums of money by recommending the right solution to the problem. If such people are not available within the company, the retaining of private consultants is a sound economic practice. The old axiom "An ounce of prevention is worth a pound of cure" is very appropriate in air pollution. It is usually much cheaper to build proper controls into the plant than to wait until the people living in the area, public officials, or both, complain and demand correction.

In assessing the potential air pollution from a new installation, consideration must be given to several factors, such as plant data, location, meteorology, and community relations.

In evaluating *plant data*, knowledge must be obtained regarding the type and amounts of contaminants to be emitted from the entire plant. It is necessary to know the particle size of the solids, and the physical properties of the pollutants, whether they are solids, fumes, gases, or mists. The characteristics of the pollutants should be determined: whether they will agglomerate, flocculate, react with other pollutants to form new substances after being subjected to sunlight. Knowledge of the toxicity of the pollutants to people, animals, and vegetation, as well as of their nuisance effects, is necessary in order to know the extent to which they should be controlled. With this information available, a study should be made of each source of emission, including the nature and volume of the effluent, the height of the stack, and the temperature of the gas, to determine if the emissions from this source will be objectionable or detrimental.

Plant location is of utmost importance in determining the extent to which pollutants should be controlled. If a plant is to be located in an agricultural area, consideration must be given to the type of crops and the effects the pollutants from the plant could have on such crops. For example, it is known that small concentrations of fluorides cause damage to gladioli. It would behoove the plant to control fluorides to a greater extent if located in an area where gladioli were grown commercially, than in a heavily industrialized area.

Topography is another factor to consider in locating the plant. Under certain meteorologic conditions, the ventilation within a valley is very poor, thereby permitting concentrations of effluents to increase.

Meteorology, especially climatology, as discussed in Section VII must be given due consideration.

Most industries today realize the importance of maintaining good *community relations*. Unfortunately, when an air-pollution problem does exist, there are usually some individuals who demand immediate action and frequently persuade the public that the plant management has little or no regard for the health and welfare of the people. If a problem does exist in an industry, it is desirable for such industry to present the facts, rather than remain aloof. This may be done by one or more of the following methods:

1. If you have an obvious problem, say so—after all, everybody can see it.
2. Make sincere attempts to control the problem.
3. Explain the problem to the employees, and keep them informed of the steps the management is taking to abate it.
4. Hold "open house," in order that people can see for themselves the problem and steps taken to alleviate it.
5. Co-operate with the press, radio and television as much as possible.
6. Help the community, through use of a technical staff, by assisting in drafting adequate and fair legislation to protect the community.

CHAPTER XIV

Occupational Dermatoses

LOUIS SCHWARTZ, M.D.

Occupational dermatoses include not only inflammations of the skin, but stigmata, traumatic injuries, chemical and thermal burns, ulcerations and proliferations caused by contact with physical and mechanical forces as well as with chemical substances encountered in the course of occupation.[1]

I. Historical Data

While Paracelsus and Agricola noted skin changes caused by salt compounds and ulcers among metal workers early in the sixteenth century, it was not until the beginning of the eighteenth century that a clear detailed description of occupational skin diseases was published. Bernardino Ramazzini (1633–1714) published *De morbis artificium diatriba,* in which he described occupational skin diseases among bakers, millers, sievers of corn, washwomen, salt miners, hostlers, bath attendants, and midwives. He attributed the dermatitis among grain handlers to an invisible parasite, a most remarkable and accurate observation when it is considered that Ramazzini did not use a microscope. Ramazzini's book remained the standard text on occupational diseases for a century, although many of his conclusions are now known to be incorrect. It was not until near the end of the eighteenth century that further observations on occupational skin diseases were published. In 1775 Percival Pott, an Englishman, stated that cancer of the scrotum occurred in chimney sweeps because of the effect of soot-soiled clothing.

There was a revival of interest in occupational skin diseases early in the nineteenth century. In England, Robert Willan described dermatitis from shoemakers' wax. Thomas Bateman described dermatitis caused by sugar and spices. He also described vesicular and pustular eruptions caused by lime. C. Turner Thackrah described dermatitis among tobacco workers and laid particular stress on personal cleanliness as a preventive of occupational dermatitis.

In France during the same period, Alibert described the dermatoses occurring among outdoor workers, caused by excessive exposure to sunlight, and the occurrence of favus among animal handlers. Rayer described pustular eruptions due to arsenic and also stated that cowpox and glanders can be transmitted to man.

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[1] General reference: L. Schwartz, L. Tulipan, and D. J. Birmingham, *Occupational Diseases of the Skin.* 3rd ed., Lea & Febiger, Philadelphia, 1957.

Ibrelile observed that infested hides can transmit anthrax to man and advocated their sterilization with boiling water. Other French dermatologists and the occupational dermatoses described by them during this period were: Potton, dermatitis among silk winders; Lespian, dermatitis caused by coal tar; Recourt and Chevalier, dermatitis caused by potassium bichromate. Bazin in 1862 published a classification of the causes of occupational dermatitis.

In Germany the outstanding contributors to the literature on occupational dermatoses during the nineteenth century were Casanave, Schedel, Von Blandit, Hebra, Eulenberg, and Hirt.

European legislators about this time inaugurated compensation laws first for industrial accidents, then for certain industrial diseases including dermatoses. After 1900 the interest in Europe concerning occupational dermatoses increased and there were noted contributions to the literature by such eminent dermatologists as Blaschko, Jadassohn, Bloch, Mayer, Oppenheim, McLeod, Sequira, Percival, and Prosser-White.

In the United States there was but little interest in occupational dermatoses before World War I. There were only a few scattered contributions by a few American dermatologists, Hazen and Lane especially.

During and after World War I there was a great increase in industrial activity in the United States, resulting in more occupational dermatoses and the subject became of greater interest to dermatologists. Contributions to the literature were made by such men as Gardner, Fordyce, Lane, Foerster, Downing, White, Sulzberger, and others.

In 1928 the United States Public Health Service organized a section for the study of occupational dermatoses. Since then interest in the subject has increased greatly in the United States; the literature now abounds with new observations and our compensation laws are including occupational dermatoses among the compensable diseases. At the present time all states have laws under which compensation for certain occupational dermatoses may be obtained.

II. Incidence

The records of state boards of health and state compensation boards have been showing a yearly increase in the number of cases of occupational dermatoses. This is largely the result of educational work among physicians and enforcement of reporting laws. For instance, in 1933, the Connecticut compensation board reported 386 cases of occupational dermatoses and none were reported by physicians, whereas in the month of December, 1943, alone there were reported nearly 400 cases, and during all of 1943 nearly 2000 cases. Of the 2000 there were less than 300 reported by the compensation board, showing that the number of cases of occupational dermatitis sufficiently severe to cause absence from work of one week or more is not increasing, but that physicians are reporting the cases they are treating. California in 1933 reported 1150 cases of occupational dermatoses whereas in 1943 there were close to 5000 cases reported. The reasons are the same as given for Connecticut.

Conservative estimates of an annual incidence of 30,000 cases of occupational dermatoses in the United States are now known to fall far short of the actual number. Our examinations in factories show that, any time a survey is made, more than 1 per cent (sometimes 10 to 15 per cent) of all the workers have occupational dermatoses. Of 60 million workers this would give a conservative estimate of at least 600,000.

The annual loss in time from work plus cost of medical care, compensation, and civil court awards for occupational dermatoses approximates 100 million dollars annually.

III. Causes of Occupational Dermatoses and Their Classification

The most frequent cause of occupational dermatoses in the United States is petroleum oils and grease. This is not because these are more powerful skin irritants than other chemicals, but because more workers are exposed to their action than to any other class of irritant chemicals. Practically all machine tools use cutting oils and lubricants. Next in etiologic frequency are the volatile solvents, alkalies, plants, and materials encountered in metal plating. With our entrance into World War II, dermatitis from explosives ranked in frequency with those in the above list. This, of course, ceased with the war.

In the course of our studies in the various industries we have found the highest incidence of occupational dermatoses among workers engaged in the manufacture and use of the resins containing formaldehyde, such as the phenol-formaldehyde resins, and among workers engaged in the manufacture of chemicals and dyes.

A. PREDISPOSING CAUSES

The cornified cells of the epidermis, the pigment, and the secretions of the skin glands constitute the defense of the skin against the action of external irritants. The cornified cells are attacked by strong alkalies, but will withstand the action of fairly strong acids and some solvents.

The secretions of the skin, consisting principally of water, liquid waxes, and cholesterol, act as diluents to water-soluble skin irritants as well as forming a protective coating against them. The pigment of the skin, melanin, aids to protect against the action of light. The perspiration, however, sometimes aids the action of irritants by macerating the skin, and by dissolving solid irritants and thus permitting them actually to come in contact with the skin.

The openings in the skin, the ducts of glands and the hair follicles, are the vulnerable portions because through them irritant chemicals that do not affect the cornified cells may penetrate the skin. Thinning of the cornified layer and breaks in the skin such as are caused by wounds and lesions of skin diseases also offer portals of entry for external irritants.

The following are the principal factors concerned with predisposition to the action of external irritants and therefore to occupational dermatoses.

1. Race

Certain industries, such as those manufacturing or using coal tar and its heavy distillates, prefer to employ Negroes because they seem to be less susceptible to skin irritation caused by these substances. This does not mean that Negroes employed in such industries do not have dermatitis. We have seen keratotic changes and even photosensitivity in the skin of Negroes working with coal tar. We know that corrosives, strong alkalies, and volatile solvents cause dermatitis in Negroes as well as in whites.

However, different types of skin do differ in sensitivity to external irritants. Blonds are more susceptible to solar radiation than are brunettes. Oily skins withstand the action of volatile solvents better than do dry skins. Hairy skins are more apt to develop oil folliculitis than are hairless skins. Different portions of the skin of the same person differ in susceptibility to external irritants. Where the keratin layer is thinnest, there is the greatest susceptibility. The palms and soles are but seldom affected by industrial skin irritants. Trinitrotoluene is an exception to this.

2. Age

Young workers, new on the job, are more frequently affected with acute occupational dermatoses. This may be because they may be less careful than older workers or because they may have not yet become "hardened." If new workers develop dermatitis they do so usually during the first month after beginning work. The chronic allergic eczematoid type of occupational dermatitis usually affects workers who have worked for many years without trouble. It seems as if they had lost their "hardness."

3. Sex

Women, as a rule, are more cleanly in their habits than men. Therefore they do not develop severe occupational dermatoses as frequently as do men. Women notice and ask treatment for the slightest skin irritation, such as most men will not even notice. Hence, the women workers may seek medical advice for skin irritations more frequently than men. The records of compensation boards show far fewer claims for compensation among women than among men, this despite the fact that women are now engaged in most occupations in which there are marked skin hazards.

4. Season of the Year

Because less clothing is worn in warm weather and because there is more perspiration, occupational dermatitis is more prevalent in most industries during the summer than the winter. On the other hand, occupational dermatitis may be more prevalent in the winter in those industries where cleansing showers after work are required in order to prevent dermatitis; this happens because workers are less likely to take the required shower after work in cold weather.

5. Perspiration

While perspiration acts as a diluent for external irritants, it also may act as a wetting agent and enable solid irritants to wet or contact the skin and so cause dermatitis. Excessive perspiration, especially if combined with friction, may so macerate the skin as to make it specially vulnerable to the action of irritants. It may also cause such changes in a chemical as to make it a skin irritant: for instance, perspiration slakes dry lime forming calcium hydroxide, a powerful alkali, and generating heat, thus causing either ulcers or dermatitis. The pH of the perspiration affects its ability to act as a solvent and hence may serve as a predisposing cause of dermatitis; thus, the diet may predispose to occupational dermatitis as it influences the pH of the perspiration.

6. Presence of Skin Disease

Workers having other skin diseases are more likely to be affected with industrial dermatitis because open skin lesions offer but little resistance to the action of external irritants. A person who is allergic to one substance is not necessarily more likely to become allergic to other dissimilar substances than one who is not allergic at all. In other words, monoallergy does not predispose to polyallergy. If this were not true, there would be a large percentage of the population who would be polysensitive because certainly a large percentage of the population is sensitive to some one substance.

7. Uncleanliness

This is probably the most important predisposing cause of occupational dermatitis. Uncleanliness of the working environment exposes the worker to large doses of external irritants. Personal uncleanliness not only does the same, but also permits the external irritants to remain in prolonged contact with the skin. Workers wearing or carrying to their homes their dirty work clothes may even cause dermatitis in other members of the family who come in contact with the soiled clothes, or even among unsuspecting laundry workers who clean them.

8. Allergy

Hypersensitivity of the skin may be divided into three etiologic groups: (*1*) hypersensitivity due to long-lasting defects in the defense mechanism of the skin, such as thin, dry, and senile skin, that permit the easy entrance of external irritants to the reactive tissue of the skin; (*2*) hypersensitivity due to temporary exhaustion of the defense mechanism, such as delay in the replacement of epithelium and depletion of the protective skin secretions; and (3) hypersensitivity in which there are no apparent defects of the skin mechanism and which is acquired by exposure and requires a period of incubation of at least five days before manifesting itself by dermatitis—a phenomenon requiring the action of the mechanism of allergy and the presence in the body fluids of histamines, reagins, antibodies, and so forth, the phenomenon for which Von Pirquet coined the term "allergy." If all three of these classes of hypersensitivity are included in the term "allergy" (which they should not be) then a large percentage of occupational dermatoses are caused by it. But if only the third type of hypersensitivity is to be termed "allergy" (as it should be) then only a small percentage of occupational dermatoses are truly "allergic." Many cases of acute allergic dermatoses occurring among young new workers clear up if the workers continue on the job and observe reasonable precautions. They become hyposensitive or "hardened." It seems that first exposure sensitizes them, continued exposure causes dermatitis, and further exposure causes a hyposensitization, or relative but not absolute immunity. Exposure to higher concentrations of the occupational allergen may again cause an eruption, but in most instances the workers upon continued exposure will develop a hyposensitivity to the higher concentrations. This does not go on indefinitely. A concentration can be reached so high that few, if any, workers can become immune to it. Hyposensitivity acquired by exposure lasts only a limited time after exposure ceases, in some cases only two to four weeks. If the worker stays away from work for that length of time he may again, upon resuming work, have to go through the same "hardening" process. Old or middle-aged workers who first develop dermatitis after many years of work with allergenic substances do not, in most instances, become "hardened." They seem to have lost the immunity they had and do not reacquire it. Such workers should change to a job where they have no contact with the offending substance.

B. ACTUAL CAUSES

The actual causes of occupational dermatoses may be divided into mechanical, physical, and chemical.

1. Mechanical

Mechanical causes of occupational dermatoses consist of: pressure; friction causing skin irritation, calluses, and keratogenic changes; cuts and abrasions, which may become the sites of secondary infections or sites of such skin diseases present on other parts of the body as psoriasis and lichen planus (Koebner phenomenon).

2. Physical

Physical causes of occupational dermatoses are heat, cold, and radiation. Heat may cause excessive perspiration at sites of friction such as the axillae, the groin, underneath the breasts, and so on, with resulting intertrigos. It may also cause burns and telangiectases such as occur in stokers and still cleaners. Cold may cause frostbite among outdoor workers. Radiation from the sun causes sunburn, herpes, and epithelioma, as occurs among sailors and farmers. Electricity can cause occupational burns among linemen. Radium has been known to cause cancer among workers who mine pitchblende and other radioactive ores, luminous-dial painters, radiologists, and technicians using radium. X-rays have caused occupational burns and cancer among makers of x-ray apparatus and among physicians and technicians.[2]

3. Chemical

Chemical causes of occupational dermatoses may be divided into primary irritants and sensitizers and each of these may again be divided into inorganic and organic.

Primary irritants. A primary skin irritant is one that causes dermatitis by direct action on the skin at the site of contact if it is permitted to act in sufficient concentration or quantity for a sufficient length of time. A primary skin irritant has a direct chemical or physical action on the skin, combining with it to form new compounds or abstracting from the skin some of its essential constituents. Some primary skin irritants may be sensitizers also.

Primary skin irritants affect and denature the skin in one or more of the following ways: they (*a*) dissolve the keratin (alkalies, soaps, sulfides); (*b*) dissolve or emulsify fat and cholesterol (the organic solvents and alkaline detergents); (*c*) precipitate the proteins (tanning agents and salts of heavy metals); (*d*) are oxidizers (bleaches and per salts); (*e*) are dehydrators (inorganic acids and anhydrides and hygroscopic chemicals); (*f*) are reducing agents (some organic acids and sulfides); (*g*) are keratogenic in their action (coal tar and petroleum). Several examples are listed in Tables 1 and 2.

TABLE 1

Examples of Primary Irritants

Inorganic acids	Alkalies	Elements and salts
Arsenious	Sodium and potassium	Aluminum sulfate
Chlorosulfonic	Hydroxide	Ammonium
Chromic	Carbonate	Antimony sulfide
Hydrofluoric	Peroxide	Chloride
Hydriotic	Silicate	Oxide
Hydrobromic	Cyanide	Arsenic, arsenates, and alkaline earth salts of arsenious acid
Iodic	Sulfide	
Hydrochloric	Hypochlorite	Bromine
Hydrofluosilicic	Calcium oxide	Cadmium cyanide

(*continued*)

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[2] For skin hazards in atomic industry, see chapter by W. D. Norwood, M.D., in Schwartz, Tulipan, and Birmingham, *Occupational Diseases of the Skin,* pp. 166–233.

TABLE I (*continued*)

Inorganic acids

- Nitric
- Perchloric
- Phosphoric
- Stannic
- Sulfamic
- Sulfuric
- Sulfurous
- Tungstic

Examples of organic acids and anhydrides

- Acrylic
- Acetic
- Carbolic
- Chloroacetic (mono-, di-, tri-)
- Cresylic
- Formic
- Acid H. (aminonaphtholdisulfonic)
- Acid J. (aminonaphtholdisulfonic)
- Acid Koch (naphthylaminetrisulfonic)
- Lactic
- Maleic
- Naphthenic
- Orthochlorobenzoic (para)
- Oxalic
- Phenolsulfonic
- Phthalic
- Salicylic
- Tobias acid (2-naphthylamine-1-sulfonic acid)
- Vinylacetic
- Vinylacrylic

Alkalies

  - Hydroxide
  - Hypochlorite
  - Chloride
  - Cyanamide
- Cement (building)
- Soaps
- Trisodium phosphate

Materials having keratogenic action

- Radiation
  - Solar[a]
  - X-ray, radium, and radioactive substances[b]
- Trauma
  - Long-continued irritation
  - Cancer arising from cicatrices
- Soot[c]
- Petroleum: crude and high-boiling fractions
- Coal tar: crude and high-boiling fractions
- Benzidine
- α-Naphthylamine
- β-Naphthylamine
- Chromium
- Some synthetic dyes, such as amidoazotoluene have been reported to cause cancer

Elements and salts

- Chlorine
- Chromium and alkaline bichromates
- Iodine
- Mercury, mercuric chloride, nitrate, cyanide
- Phosphorus
- Potassium
- Radium
- Selenium
- Sodium
- Tin chloride
- Zinc chloride

Aldehydes and amines

Formaldehyde and most other aldehydes are primary irritants, as are most of the amines

[a] Outdoor workers. [b] Physicians, technicians. [c] Chimney sweeps.

TABLE 2

Examples of Primary Irritant Solvents

Turpentine group

(Compn. varies, mainly, dextro and levo pinenes)

- Turpentine
- Wood spirit
- Pine oil

Petroleum solvents and oils

- Gasoline
- Cymogene or rhigolene
- Pentane
- Petroleum ether
- Petroleum spirit (ligroin)

Chlorine derivatives

- Methylene chloride
- Chloroform
- Carbon tetrachloride
- Dichloroethylene
- Trichloroethylene

TABLE 2 (*continued*)

Turpentine group

Pine needle oil
Oil of spike
Terpineol
Rosin spirit
Tar spirit

Coal tar group

Benzol
Light solvent naphtha
Heavy solvent naphtha
Xylol
Cyclohexane
Tetralin
Decalin

Alcohols

Methyl alcohol
Ethyl alcohol
Butyl alcohol from mash
Amyl alcohol from petroleum
Propyl alcohol from petroleum
Benzyl alcohol from toluene
Cyclohexanol from cyclohexane

Petroleum solvents and oils

Benzine
White spirit
Petroleum oils

Esters

Methyl acetate
Ethyl acetate
Amyl acetate
Butyl acetate
Methyl formate
Ethyl formate
Butyl formate
Amyl formate

Ketones

Acetone
Methyl acetone
Methyl ethyl ketone
Methyl cyclo hexanone

Chlorine derivatives

Perchloroethylene
Tetrachloroethane
Pentachloroethane
Monochlorobenzene
Dichlorobenzene

Resin solvents

Dichlorohydrin from glycerol + hydrochloric acid
Epichlorohydrin from glycerol + hydrochloric acid + acetic acid

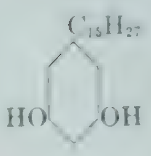
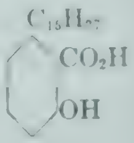
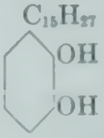
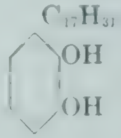
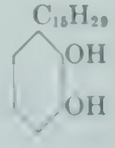
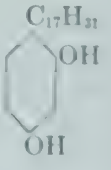
Carbon disulfide

Sensitizers. Sensitizers do not necessarily cause demonstrable skin changes on first contact, but effect such specific changes in the body or skin that, after five days or more, further contact on the same or other parts of the body will cause dermatitis. It is impossible to give a complete list of sensitizers because some people may be sensitive to substances to which the large majority are not, for instance, heat, cold, wool, silk, etc. Substances that sensitize to sunlight are called photosensitizers.

Plants causing dermatitis (primary irritants and sensitizers). Although plants such as nettles are primary skin irritants, and those with thorns cause skin wounds, most plants that cause dermatitis are sensitizers. The principal irritants in the plant group belong to the family *Anacardiaceae.* They produce allergic dermatitis and many workers develop "hardening" upon continued occupational exposure.

TABLE 3

Irritant *Anacardiaceae* (According to Haack)

Botanical name	Encountered as	Active ingredients	Formula[a]
Anacard. occidentale Linn.	Cashew nut shell	Cardol	
		and	
		Anacardic acid	
Pentaspadon Motleyi Hook f.	Japan and Chinese lacquers	Cardol	
Rhus vernicifera		Urushiol	
Rhus succedanea Linn. f.	Indo-China lacquer	Laccol	
Rhus ambigua Lav. (= *R. orientalis Schn.*)		Laccol	
Rhus toxicodendron Linn. (= *R. radicans* = *R. diversiloba*)	Poison ivy	Urushiol	
Rhus venenata (= *R. vernix*)	Poison sumac	Urushiol	
Semercarpus anacardium Linn. f.	Marking nut	Bhilawanol (= urushiol)	
Semecarpus heterophylla Bl.		Renghol	
Semecarpus albescens Kurz.			
Semecarpus cassuvium Roxb.			
Semecarpus Forsterii Bl.			
Semecarpus vernicifera Linn.	Formosa lacquer	Laccol	
Mangiferra indica Linn.			
Mangiferra caesia Jack.			
Mangiferra foetida Lour.			
Mangiferra odorata Griff.			
Gluta rhengas Linn.	Burma lacquer	Renghol	
Gluta velutina Bl.			
Melanorrhoea usitata. Wall.		Thitsiol	
Melanorrhoea wallichii Hook f.			
Melanorrhoea curtisii Oliv.			
Melanorrhoea tomentosa Hook f.			
Melanorrhoea laccifera Pierre.			
Buchanama arborescens Bl.			
Buchanama velutina Bl.			

[a] It will be noted that urushiol, laccol, and renghol are similar compounds. Cardol and thitsiol differ in molecular structure.

Dermatitis has been reported from more than 500 different plants, of which the most frequently reported in industry belong to the *Anacardiaceae*. Some others are:

Primrose
Nettle
Spurge
Daffodil
Tulip
Cinnamon
Mango
Fig
Prickly pear
Asparagus
Chrysanthemum
Hops
Vanilla
Marigold
Cow parsnip
Wild carrot
Satinwood
Mahogany
Boxwood
Brazilian walnut
Cocobolo
Teak
Chestnut

Dermatitis is of frequent occurrence among fruit and vegetable packers and canners. The following fruits and vegetables have been reported to cause dermatitis:

Oranges
Lemons
Grapefruit
Peaches
Figs
Tomatoes
Pineapples
Mangoes
Carrots
Lettuce
Hops
Celery

Some Photosensitizers

Coal tar
Pitch
Asphalt
Creosote oil
Fluorescein
Rhodamine N.
Bergamot
Figs
Agave locheguilla
Fagopyrum esculentum (buckwheat)
Fagopyrum tataricum (India wheat)
Daucus carota (wild carrot)
Tribulus terrestes (puncture weed)
Trifolium hybridum (alsike clover)
Hypericum perforatum (St. John's wort)
Hypericum crispum (St. John's wort)
Medicago denticulata (bur clover)
Nolina texana (bunch grass)
Polygonum persicaria (lady's thumb)
Tetradynia canescena (rabbit bush)
Tetradynia glabrata (rabbit bush)

4. Biologic Agents

Biologic agents may be causes of occupational dermatitis. Bacteria may infect occupational wounds. Erysipeloid, caused by the bacillus of swine erysipelas, occurs among butchers, bone button makers, and fishermen. Butcher's pemphigus is a rare occupational disease. Impetigo, cowpox, anthrax, glanders, actinomycosis, foot and mouth disease, all may be contracted occupationally from infected animals. Verruca necrogenica, or tuberculous warts, occurs among butchers, and postmortem attendants. Tables 4 and 5 list some biologic agents that have caused occupational dermatoses.

The following moths or their caterpillar stages have been reported to have caused dermatitis among horticulturists and farmers:

Moth	Action
Brown-tail (*Euproctis*)	Hairs irritate
Gold-tail (*Liparis chrysorrhea*)	Hairs irritate
Goat (*Cassus ligniperda*)	Secretes formic acid
Puss (*Cerua vinula*)	Secretes irritant
Fox (*Chenilles processionnaires*)	Hairs irritate

TABLE 4

Parasites

Dermatosis	Causative organism	Vector
Scabies	*Acarus scabei*	Clothing, as in barracks
Pediculosis	*Pediculosis pubis*	
Pediculosis	*Pediculosis corporis*	
Mange	*Acarus sarcoptes* (or demodex)	Animals
Ground itch (uncinariasis, aukylostomiasis)	*Aukylostomaduodenale*, or *Necatur americanus*	Earth infested with hookworms
Grain itch	*Pediculoides ventricosus*	Grain or straw
Barley itch	*Sphoerogyna cerealella*	
Grocer's itch	*Carpoglyptus passularum, Tyroglyphus*	Figs, dates, prunes, cheese
Rat mite dermatitis	*Liponyssus bacoti*	
Copra itch		
Linseed itch		Beetles and parasites
Hog itch	*Ascaris*	Hog intestines
Tick bites	*Ixodes* (cattle ticks, wood ticks)	Cattle, woods
Harvest itch	Chiggers, *Leptus* (*Trombicula*) *irritans*	Grass or grain
Sand flea bites	*Chigoes*	
Fowl mite itch (Gamasoidosis)	*Dermanyssus avium*	Mite-infested birds or bird homes

TABLE 5

Fungi

Fungi	Occupation
Yeasts	Bakers, dishwashers
Monilia	Dishwashers, scrubwomen, fruit canners
Dermatophytes	Animal handlers; fur, hide, and wool workers; barbers, beauticians, bath attendants
Sporotrichum	Horticulturists
Blastomycetes	Horticulturists
Actinomycetes	Animal handlers

IV. Clinical Types of Occupational Dermatitis

Occupational dermatitis may assume the following forms:

1. Acute eczematoid dermatitis, which is characterized by erythema, edema, papules, vesicles, crusts, and desquamation. It is usually the result of a primary skin irritant or of an initial allergic dermatitis.

2. Chronic fissured eczematoid dermatitis, characterized by erythema, lichenification, cornification, and fissuring. It is usually the result of unresolved acute cases or the prolonged action of mild dehydrators, fat solvents, soaps, and detergents.

3. Folliculitis and acneform lesions, characterized by plugged sebaceous glands and suppurative inflammation of hair follicles. It is usually due to exposure to coal tar, petroleum oils, or solid chlorinated hydrocarbons.

4. Epidermal proliferation, which may be malignant or benign, characterized by keratosis, papillomata, and epitheliomata. It is usually caused by exposure to coal tar and its heavier distillates or to crude petroleum oil or to radiation.

V. Diagnosis of Occupational Dermatoses

Dermatoses affecting workers are not all occupational. Workers may also develop dermatoses from causes having no connection with their occupations. It is often necessary to prove or disprove an occupational etiology. This is necessary not only for purposes of treatment and prevention, but also for medico-legal reasons.

The diagnoses of occupational dermatoses are made on the following criteria:

1. History must show: (*a*) dermatitis did not antedate employment; (*b*) dermatitis developed during period of industrial exposure or (*c*) about 10 days after employment ceased (incubation period); (*d*) dermatitis improves away from exposure and exacerbates on reexposure.
2. Site of eruption: (*a*) first appears on exposed parts or sites of friction; (*b*) covered parts affected by penetrating dusts, fumes, and soiled clothes; (*c*) distant parts affected in allergic cases after incubation period.
3. Appearance of lesion: may be characteristic of class of irritant but not of particular irritant.
4. Patch tests: must be intelligently performed; results properly read and evaluated.
5. If a doubtful case shows no marked improvement two months after exposure ceases it is probably not of occupational origin, or is being irritated by a nonoccupational irritant.

Occupational dermatoses may have to be differentiated from nonoccupational skin disorders. The ordinary nonoccupational dermatoses, such as psoriasis, lichen planus, acne vulgaris, erythema multiforme, and pityriasis rosea, offer dermatologists no difficulties in differential diagnosis; but to differentiate from contact dermatitis caused by irritants encountered outside of the occupational environment often requires considerable investigation. The occupational history must be carefully considered and correlated with the appearance and site of the eruption. The occupational process and the chemicals contacted must also be correlated with the site and appearance of the eruption. It is often necessary to perform patch tests with sensitizing substances that the worker contacts. (*Patch tests with strong primary irritants should never be made.*) Although there are exceptions, a good rule is that occupational dermatitis improves when the worker stays away from work and gets worse if he returns to work (except where "hardening" has occurred).

The lesions of dermatophytosis and their allergic eruptions, called phytids, also offer some difficulties in differential diagnosis, especially when the lesions are on the fingers, hands, and arms. A few simple differential points follow. Occupational dermatitis rarely occurs as deep-seated vesicles on the palms or soles; the phytids often occur as such. The phytids are accompanied by fungus infections between the toes, or on the feet, or the axillae, or groin, and careful examination will in many cases result in demonstrating the causative fungus. The trichophyton test is positive when a fungus infection or phytid is present. It is negative in about 50 per cent of cases where there are no clinical evidences of fungus infection. The patch test with the occupational causative substance is positive in the active stage of the eruption. It is negative if the eruption is purely of fungus origin.

Fungus infections and phytids are in most instances independent of working conditions, and their improvement does not depend on absence from work. In differential diagnosis of occupational from nonoccupational dermatoses it is usually safe to say that if a supposed case of occupational dermatitis does not recover or markedly improve after two months absence from work, it is probably not connected with the occupation (unless it is overtreated or nonoccupationally irritated).

We must not lose sight of the fact that it is entirely possible for a worker to have a fungus infection and an occupational dermatitis at the same time.

Two controversial diagnoses appearing most frequently in compensation courts are "neuro" dermatitis and "atopic" dermatitis. The physician for the plaintiff will testify that these diseases in the claimant were caused or aggravated by his employment. In the author's opinion, the diagnosis "neuro" dermatitis is much abused and certainly cannot be caused by substances met in industry. However, it may be possible that increased tension and emotional upsets may have an adverse effect on the mental health of the patient. The lichenified eczemas that are caused by scratching are most often the result of the habit of scratching parts that may or may not have been inflamed before the scratching. After the parts become inflamed from the scratching they undoubtedly have a lowered threshold of irritation and chemicals may irritate them that would not have done so had the skin not been scratched.

The term "atopic" was applied by Coca and Sulzberger to designate a type of sensitization characterized by a familial tendency to the development of certain forms of diseases, such as children's eczema and areas of chronic lichenified eczema. "Atopic" individuals may develop a dermatitis from ordinarily innocuous substances. Atopic dermatitis is not industrial; however, an atopic individual may develop a contact dermatitis more easily than a normal individual. Workers having "neuro" dermatitis or "atopic" dermatitis may get well while at work and relapse while they are away from work. Such workers, when appearing in compensation courts, will state that, even though they have not been working in the plant for several months or years, they still develop recurrent attacks of dermatitis similar to those they had in the plant. Such a statement in itself leads the author to believe that the materials contacted in industry are not the cause of the claimant's present dermatitis. Neither does the author believe that the person sensitized to a chemical by occupational exposure becomes, as a result, sensitized to chemically unrelated nonirritating or nonoccupationally encountered chemicals.

A. THE PATCH TEST IN INDUSTRY

There has been much controversy regarding the value, proper technique, and interpretation of patch tests. The patch test was used by Jadassohn and others more than fifty years ago for demonstrating the causes of contact dermatitis. In the United States it was not widely used in industry, nor was its practical value appreciated, until after the United States Public Health Service called attention to the prevalence of occupational dermatitis, to the actual chemicals causing it, and to the value of patch tests in the differential diagnosis between occupational and other sources of contact dermatitis.

At first the patch test was used as a means of diagnosing contact dermatitis and of determining the actual causative chemical irritant. Since dermatitis among the general public has on many occasions been found to be caused by irritant chemicals contained in garments and cosmetics, manufacturers have taken advantage of the patch test to determine the possible skin irritating or sensitizing properties of new products before placing them on sale to the public (prophetic patch test).

It has even been proposed by some enthusiasts to use the patch test as part of the pre-employment examination with the idea of weeding out those workers who might develop occupational dermatitis. The fallacy in the proposal is that most workers develop their occupational dermatitis either by contact with a primary irritant or by acquiring an allergy while actually employed. Therefore, pre-employment patch testing could not weed out those who would become sensitized.

It is now universally accepted that the patch test is a valuable diagnostic procedure. Its value in preventing possible outbreaks of dermatitis from the use of materials containing new chemicals is fully recognized.

1. Technique

Before attempting to describe the methods used for patch testing, we must clearly distinguish between substances that are primary skin irritants and those that we shall call sensitizers. It is obvious that a concentrated solution of a strong acid or alkali will burn or inflame any skin, the degree of injury depending on the concentration of the irritant, the amount applied, the duration of its action, and the area of skin to which it is applied. Such chemicals actually form chemical combinations with the skin, and can be called primary irritants. There is another class of chemical that will cause inflammation of the skin if applied for a sufficient length of time: the strong solvents such as gasoline, carbon tetrachloride, chloroform, and so on. These substances abstract from the skin some of its essential components, such as the fats, resulting in inflammatory reaction. Other chemicals have different actions on the skin, such as protein precipitants, oxidizers, keratin solvents, reducing agents, and so forth; all these are primary irritants.

It is obvious that patch testing with strong concentrations of known primary irritants will result in reactions on any skin. This does not mean that patch testing should not be performed with dilute solutions of chemicals that in strong concentration are primary irritants. There are published lists of concentrations of chemicals that dermatologists have used as patch tests to determine hypersensitivity. The use of these concentrations, together with the time they are to remain on the skin, is an attempt to avoid the primary irritant action of the chemical.

While the majority of occupational dermatoses are caused by primary irritants, about 20 per cent are caused by substances that do not have a primary irritant action on the skin. These chemicals that are not primary irritants are responsible for by far the large majority of cases of contact dermatitis among the public caused by wearing apparel, cosmetics, ornaments, etc. They induce a specific skin allergy and thus cause dermatitis. They are called sensitizers. It is well known that many chemicals that are primary irritants, for instance, formaldehyde, bichromates, mercuric salts, and phenols, are also sensitizers.

The ordinary diagnostic patch test consists in applying a small portion of the suspected substance to a site of normal skin of the patient. This is covered with innocuous impermeable material, which is then sealed to the skin by adhesive plaster. There have been many modifications proposed in order to overcome certain objections.

With liquids the diagnostic patch test is performed in the following manner. Saturate a piece of four-ply gauze about $^3/_4$ inch square, and apply it to uninflamed skin on the arm or back. The liquid should not be permitted to trickle from the patch site. For insulation a $1^1/_2$-inch square piece of nonwaterproof cellophane is used. (Waterproof cellophane consists of regenerated cellulose coated with a water-insoluble resin.) This is sealed to the skin with a piece of adhesive plaster about 3 inches square; when smaller pieces of adhesive plaster are used, patches are often lost or there is insufficient contact of the test substance with the skin. The reactions that may result from the adhesive plaster are separated from those resulting from the test substance by the uninflamed skin which is in contact with the cellophane only. In performing a number of patch tests, care should be taken to avoid overlapping of adhesive plaster, which will cause intensification of the adhesive plaster reaction.

In performing patch tests with powders, the powder is placed on a piece of gauze in order to keep the reaction localized. If the gauze is moistened it holds the powder better than when dry.

In patching with solids it is not necessary to use gauze. When solids insoluble in water are used for patching we have found it best to dissolve them in a solvent making a saturated solution and wetting a piece of gauze with this solution. The gauze is then allowed to dry before placing it on the skin. This procedure deposits the precipitated finely divided substance on the gauze and thus brings about better contact with the skin. When the insoluble solid is of a resinous character, the solution may be painted directly on the skin, the solvent allowed to evaporate, and the cellophane and adhesive plaster applied. In such cases if the resin adheres firmly to the skin it is not necessary to cover it with the cellophane and adhesive. The technique of patching with ointments is the same as for liquids.

While solvents are primary skin irritants, they sometimes also act as sensitizers. When it is desired to find out whether a solvent is causing dermatitis by its action as a sensitizer, patch tests may be performed as follows: mix equal parts of the solvent with equal parts of a bland oil such as liquid petrolatum or corn oil, in order to buffer its primary irritant action, and patch as for liquids.

It is usually sufficient to leave the patch on for 24 hours, but sometimes when patching with low concentrations or with weak sensitizers it may be necessary to leave the patch on for three or four days. (Do not leave on more than five days; the patient may by that time become sensitized to the patch.) This is especially true of fabrics that contain no strong irritants and to which most people do not react. The reactions should be read not only upon the removal of the patches but every day for at least five days thereafter. This is of special importance in testing fabrics.

It is sometimes advisable to use a so-called artificial perspiration to moisten the test substance because the H-ion concentration of the perspiration, especially in such areas as the axillae, may play a role in the solubility of the irritant under investigation. The pH of axillary sweat is usually on the alkaline side and that on the body proper is on the acid side; pH can vary from 5 to 8. To approximate the pH of the perspiration, acidify water with acetic acid and alkalinize another sample with ammonia.

2. Interpretation and Reading of Patch Tests

It requires considerable experience to interpret correctly the reactions produced by patch tests. Since the patch test was first introduced, grading of the patch test reactions has been attempted in ranges between 1+ and 4+. For instance, a 1+ reaction indicated an erythema on the area of skin to which the chemical was applied; a 2+ reaction indicated erythema and edema; a 3+ reaction indicated an erythema, edema, papules, and a few vesicles; a 4+ reaction indicated erythema, edema, many vesicles, and even ulceration.

Such a method of recording a positive patch test is useful perhaps in indicating the degree of sensitivity to the specific concentration and amount of the chemical used. Additional information and interpretation can be obtained if patches with differing concentrations are applied. The degree of reaction will be greatest at the site of greatest concentration. Reactions that are not present when the patch is removed but become manifest less than five days after the patch was applied are delayed reactions. Delayed reaction means either that there is present a low degree of specific sensitivity or that a weak concentration of the sensitizer was used.

The true allergic reaction as a rule increases rather than decreases in intensity for 24 to 48 hours after the patch test is removed. Reactions of primary irritation with few exceptions tend to subside after the removal of the irritant.

The evaluation of a weakly positive reaction (1+) depends a great deal on the experience of the one reading the patch test. In dealing with a fabric or other substances containing a weak concentration of a sensitizer, a 1+ or 2+ reaction is significant. This is especially true in industry where not only is a dermatitis due to contact with the sensitizer in low concentration, but where there may also be the added factor of friction, with exposure to larger amounts of the chemicals than present in the patch test.

A positive reaction that cannot be reproduced with the same technique indicates that at the time the original patch test was performed the patient was sensitive to the concentration and quantity of chemical applied. A 1+? reaction not persisting for 24 hours is probably a false positive. A negative patch test does not necessarily rule out the test substance as a causative agent. The negative reaction might be due to the fact that: *(1)* under the condition of the patch test the actual mechanism that produces the dermatitis is lacking, that is, the patch test does not equal working conditions; or *(2)* the patient is no longer sensitive; or *(3)* the actual sensitizer was not applied.

The impression seems widespread that patch tests should not be performed while an eruption is still present because a flare-up of the dermatitis might take place. The most favorable period, when a positive patch test can be expected, is at the time that the dermatitis is still present. A relative hyposensitivity may develop when the dermatitis disappears, with the result that the patch test would tend to be negative. Here, too, experience and judgment are necessary to choose the proper time for performing patch tests. Obviously, when dealing with a patient who has a generalized dermatitis it is better to wait until the eruption has improved before performing a patch test and, when it is carried out, a low concentration of the suspected chemical should be used. A generalized eruption may mean either that we are dealing with a high degree of sensitivity, or a massive exposure of a person who may be only moderately sensitive.

In cases with true allergic dermatitis, the skin all over the body is sensitive and patch tests can be applied at any convenient site. The most rapid reaction, all other factors being equal, will take place in areas of skin where the keratin is thinnest. The thick keratin layer of the palms and soles not only explains the negative patch test that results at these sites, but is the main reason why contact dermatitis is rarely seen in these locations.

3. Complications of Patch Tests

Unless inadvertently a patch test is made with a primary irritant, even strongly positive reactions rarely leave a scar. In the presence of marked hypersensitivity, patch testing with a fairly high concentration of the allergen may produce a skin reaction that spreads beyond the area of application of the patch or it may elicit a generalized reaction. This generalized reaction may manifest itself either as a flare-up of existing lesions, reappearance of lesions that have already faded, or the appearance of a generalized eruption. Such a complication may occur even when a standard concentration of the sensitizing chemical is used for the patch test. This last, however, is rare. Toxic symptoms from absorption of the patch test material are unlikely because of the small amounts of chemical used and the relatively small area of skin through which absorption is possible. However, such rare instances have been reported. Systemic symptoms, such as a rise in temperature, adenopathy, and pain, have sometimes occurred after patch testing.

Patch tests are of established value in the determination of the etiologic agents in dermatitis venenatum, and are accepted by many insurance companies and compensation boards as necessary steps in establishing a causal relationship.

Patch tests should not be performed with allergens with which the patient has not already come in contact and which he may later encounter frequently in the course of his daily life, because of the possibility of inducing a hypersensitivity, with a resultant dermatitis the next time he comes in contact with the allergen.

VI. Prevention of Occupational Dermatoses

Until recently there has not been as much attention paid to the prevention of occupational dermatitis as to the prevention of occupational poisonings, despite the fact that there is more time lost from work on account of occupational dermatitis than any other occupational disease. If a chemical irritates the skin, it may also affect the entire system. Protecting the skin may save the whole body.

Unlike the protective measures taken against systemic occupational diseases, which are practically the same for nearly all—reduction of the concentration of the poison in the air by enclosed processes and exhaust systems—the same method of prevention will not suffice for all of the various skin irritants encountered in our industries. There are many protective measures against the different sources of industrial skin irritants.

A. PRE-EMPLOYMENT EXAMINATIONS

Protective measures should begin in the pre-employment examination, when the dermatological history of the applicant should be carefully elicited, and the skin should be examined and the pathologic conditions found should be noted on the examination card. Applicants with a history of atopic and neuro dermatitis and those found to have skin eruptions should not be employed in occupations where there is a marked skin hazard. For instance, they should not work with such well-known sensitizing chemicals as the explosives, formaldehyde, chromates, and dye intermediates.

Pre-employment patch testing for the purpose of discovering those persons who are allergic is not advisable. Because people are not allergic to chemical allergens with which they have had no previous contact, few allergies, if any, would be discovered by patch testing among applicants not previously exposed to these chemicals. Patch testing persons with sensitizing materials may be the means of sensitizing them. Moreover, applicants found by patch tests to be sensitive, and therefore rejected, may have a legal claim against the company for having been given the skin eruption that otherwise they would not have had. There is, however, some basis for patch testing with the common allergens that cause so-called "atopic" dermatitis (house dust, flour, etc.) to discover atopic individuals, although careful history-taking can bring out the fact of whether the person is or is not "atopic."

Careful note should be made of the sites of acne vulgaris lesions on applicants for work in occupations in which they are to be exposed to such occupational acne producers as the solid chlorohydrocarbons, cutting oils, heavy coal-tar distillates, crude petroleum, and lubricants derived from it.

The presence of active mycotic infections on the feet and other parts of the body should be noted. If the applicants are otherwise employable, the fungus infections should be treated while they are working, and the parts affected should be properly protected from the action of occupational irritants. If there are common shower baths in the factory, care should be taken to prevent the spread of fungus infections of the feet. This can be done by providing each worker with wooden-soled bathing slippers, and he should be instructed to wear these when going to the shower bath, while he is under the shower, and when coming from it. It is not sufficient to have antiseptic solutions in troughs into which the workers are required to step after they have taken their showers, because walking barefooted from the troughs to the lockers allows plenty of opportunity for them to pick up or spread the infection. The workers should also be instructed to dry the feet thoroughly and spread powder between their toes before putting on their stockings. The fungi do not grow in dry media. There are many powders on the market for this purpose, and most of them contain some antiseptic, such as oxygen in the form of perborates and peroxides, and other fungicidal chemicals.

Applicants who have dry skins should not be placed on jobs where they must immerse their hands in fluids that defat the skin, such as strong soaps, alkalis, solvents, or solutions of industrial skin irritants.

B. VENTILATION

Efficient ventilation is of great value in protecting the employees from industrial skin irritants (for discussion of ventilation, see Chapter X).

C. PROTECTIVE CLOTHING

Properly designed protective clothing is of great value in the prevention of occupational dermatitis. Closely woven cotton fabrics that are more or less impervious to dust are frequently used to protect workers from such irritant dusts as sodium carbonate, calcium cyanamide, and others. To give efficient protection, such fabrics must be frequently cleaned. Each worker should have at least two sets of work clothes, so that he will have a clean set to wear while the other is being laundered. It has been found best to have the management of the plant undertake the laundering of such clothes because the worker himself is often loathe to spend the money. In one plant where such was the practice, it was estimated that it cost the plant about ten cents per day to furnish daily clean work clothes for each worker.

Impervious materials, such as rubber, offer better protection against dusts than do fabrics, and they also give protection against irritant liquids. Rubber gloves, aprons, boots, and sleeves are impervious to water-soluble irritants. Rubber, however, soon deteriorates when exposed to alkalies, petroleum distillates, or the chlorohydrocarbon solvents. For this reason it is rather expensive to use in occupations in which it comes in contact with these chemicals. Synthetic rubbers, such as Neoprene, Buna-N, and Buna-S, are more resistant to alkalies and oils than is natural rubber. However, workers often object to wearing rubber garments; some state that rubber causes them to perspire excessively, and some of them are allergic to compounds in the rubber.

We have found that some of the synthetic resin films, such as Pliofilm (manufactured by Goodyear Tire & Rubber Co., Inc.), Koroseal (manufactured by The B. F. Goodrich Co.), and Vinylite (manufactured by Union Carbide & Carbon Corp.), are impervious not only to dust and fumes, but also to strong acids, alkalies, and petroleum distillates.[3] These materials may be made into sleeves, aprons, hoods, and coveralls, and experimentally they have even been made into gloves. They are comparatively cheap, are nonflammable, may be easily cleaned with soap and water, and are translucent. This last property removes the psychologic effect of feeling confined. It is true that these substances, like rubber, prevent the circulation of air on parts of the body that they enclose, but this can be overcome by placing vent holes in the upper parts of the sleeves and in the rear of the coveralls, where such holes are not likely to allow the entrance of irritants. We have found that these films also give good protection against vesicant gases. They can be made with such tensile strength that, when worn as sleeves by machine operators, they will tear if caught by cogs before they can draw the arm of the worker into the machinery.

These films are affected by trichloroethylene and carbon tetrachloride and, therefore, are not suitable for protection against these substances. The polyvinyl alcohols are proof against trichloroethylene and carbon tetrachloride. They are manufactured in the form of gloves and called by the trade name Resistoflex. The polyvinyl alcohols are affected by water and, therefore, Resistoflex gloves should not be exposed to it. They may be cleaned with the volatile solvents.

Celanese and cellophane can be plasticized with glycerin to form a pliable film capable of being made into protective clothing. They are not affected by acids or petroleum solvents. Cellulose acetate films are water-insoluble and make suitable protective clothing.

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[3] L. Schwartz, H. Warren, and F. Goldman, *U. S. Pub. Health Repts.*, **55**, 1158 (1940).

Leather gloves offer good protection against trauma and irritant or sensitizing solids and dusts. Leather gloves should be made of soft pliable, washable leather, such as chamois. The seams should be finished and smooth. Coarse seams rub and irritate the skin, causing dermatitis not only by mechanical friction, but by rubbing into the denuded skin the irritant chemical particles that have fallen into the glove at the wrist opening. Gloves for the protection of the hands from irritant chemicals should reach well up the forearms and should be worn under impervious sleeves fastening at the wrists so as to prevent the entrance of irritant chemicals into the gloves. Aprons should reach well up to the neck and down below the knees. Aprons are of special value in protecting the body from cutting oil. The fact is again emphasized that protective clothing, to be really protective, must be cleaned daily and kept in good repair.

D. CLEANLINESS

Cleanliness is by far the most important single measure for the prevention of industrial dermatoses. By cleanliness, we mean not only cleanliness of the person, but cleanliness of the room, the machines, and the clothes. Floors, walls, and ceilings of rooms in which there are industrial irritants should be wet-cleaned daily. Machines and tools on which industrial irritants are deposited also should be cleaned daily. Adequate washing facilities should be provided for workers handling industrial skin irritants. Workers whose clothes become soiled with industrial skin irritants should be compelled to take supervised shower baths after work, before leaving the factory. It may be necessary to have a double set of locker rooms to be sure that workers do not put on dirty clothes before going home. Care must be exercised so that the soaps and other cleansers used by workers to remove dirt, dyes, oils, etc., will not themselves cause dermatitis. Workers who become soiled with oils, greases, and dyes are likely, if left to themselves, to use the most available and most rapid-acting solvent to clean the skin. They do not stop to consider the irritant action of the cleanser. Many cases of dermatitis among workers have been caused by the cleansers used to clean up before going home. Safety engineers should see that workers use only such cleansers as will not act as skin irritants.[4]

In certain occupations where irritants must necessarily come in contact with the worker's skin, such as in shops where irritant resins are used for laminating, or where irritant or sensitizing solutions such as bichromates contact the skin, it is advisable to install strategically placed wash basins 100 feet apart. Then, no worker need walk more than 50 feet in order to remove irritant chemicals from the skin. Such washstands should be equipped with hot and cold running water, a suitable dispenser for industrial soap or sulfonated oil, and paper towels. Such installations will discourage the use of solvents and strong industrial metal-cleansing solutions to remove soil from the skin. An antiseptic with a low sensitizing index, such as G-11, incorporated into the soap or other cleanser is of value in the prevention of occupational pus infections of the skin, such as cutting-oil boils and other types of industrial pyodermia. Recently, it has been found possible to incorporate a nonirritating form of iodine into industrial cleansers giving them good antiseptic properties. The addition of a certain amount of lanolin, cholesterol, or lecithin to soap tends to lessen the defatting action on the skin.

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[4] L. Schwartz, *Med. Clinics N. America*, **26**, 1195 (1942).

Waterless hand cleaners are now on the market. Many of them are creams, consisting essentially of a soap and a petroleum solvent, and carbon tetrachloride also may be contained in some of them. Compositions such as the above will cause dermatitis if used frequently during the workday. Some of the waterless hand cleansers do not contain solvents; instead they contain as active ingredients the synthetic wetting agents and sulfonated oils. Such compositions are less likely to cause dermatitis. The waterless hand cleansers are ultimately washed off with soap and water at the end of the day or before lunch. Waterless hand cleansers should be used temporarily to remove soil pending the installation of adequate washing facilities and should not be a substitute for them.

An industrial cleanser for the normal skin should have the following qualities: it should be freely soluble in hard, soft, cold, or hot water; it should remove foreign soil, fats, and oils without harming the skin; it should not contain harsh abrasives or irritant scrubbers; it should be handy to use in cake form, or should flow easily through soap dispensers if in granulated powder or liquid form; it should not deteriorate or become insect-infested.

For those occupations in which excessive scrubbing with such a soap is necessary in order to remove dyes or tenacious oil, it may be better to add to such a cleanser a small amount of alkali, such as trisodium phosphate. Whenever such alkali-reinforced cleansers are used, it is best to supply the worker with an emollient cream to be rubbed into the skin after washing to replace the fat removed by the strong cleanser.

Workers who have dermatitis, or sensitive or dry defatted skins, should not use the ordinary industrial cleanser previously described. It is better for them to use one of the soapless cleansers, the pH of which is 7 or less. Such a cleanser may consist of a neutral sulfonated castor oil containing from 1 to 2 per cent of the synthetic wetting agents. The cationic wetting agents also have marked germicidal powers and are said to leave persistent germicidal films on the skin. They have the disadvantage of being incompatible with soap.

E. PROTECTIVE OINTMENTS

While protective ointments are low on the list of preventive measures, they are often the only available means of protection. In most occupations the face cannot be covered by protective clothing. Often the work must be performed with bare hands, gloves being unsuited for the operation. Workers, as a rule, dislike to wear protective clothing but seem to have a particular liking for the use of protective ointments. When a protective ointment is used, the worker invariably washes it off with soap and water immediately after work, and so removes not only the ointment but whatever irritants there are on the skin. This washing after work adds considerably to the value of the protection supposedly given by the ointment.

There is no one formula for a protective ointment that will give efficient protection against all skin irritants. However, all protective ointments should have the following properties: they should be nonirritating and nonsensitizing; they should give actual protection from the irritant; they should be of such consistency that they can be easily applied; they should stay on while the worker is exposed to the irritant and yet be easily removable after work.

Protective ointments may be divided into three main classes:

1. The simple vanishing-cream type, which fills the pores of the skin with soap and facilitates the removal of soil during washing after work because the soap in the pores, when washed away, tends to remove soil from within outward onto the skin.

2. The water-repellent type of ointment, which leaves a thin film of a water-repellent substance, such as lanolin, spermaceti, carnauba wax, beeswax, petrolatum, shellac, ethyl cellulose, or silicone, on the skin, thus preventing water-soluble irritants, such as inorganic acids or alkalis, from contacting the skin.

3. The oil-repellent type of protective oil, which may contain substances, such as sodium alginate, methyl cellulose, sodium silicate, tragacanth, acacia, or casein, that repel solvents and oil. Lanolin, which also has oil-repellent as well as water-repellent properties, is often included in this type of ointment because of its skin-emollient properties.

The silicones are widely advertised as skin protectives against all types of irritants, but actually they do not protect against solvents, although some of them, especially the greasier ones, have good water-repellent properties. Tests in laboratories, however, have shown that both lanolin and petrolatum form as good water-repellent films on the skin as do the silicones. It seems that the more the silicones are compounded in order to make protective creams cosmetically acceptable, the more impaired is their water repellency.

In addition to these three main classes, there are protective ointments that contain chemicals intended to detoxify the particular industrial irritant. For instance, protective creams against acids may contain alkalies, such as soap and magnesium hydroxide. A protective cream against poison ivy may contain an oxidizing agent, such as sodium perborate, to detoxify the active toxic principle "Urushiol." There are also protective ointments that contain inert powders that adhere to the skin forming a mechanical barrier covering. The powders incorporated in such creams or films may be calamine, zinc oxide, iron oxide, titanium oxide, bentonite, and others. The cream may also contain an adhesive binder, such as one of the resins, to make the powder adhere. Such ointments are of value in protecting against such allergenic substances as TNT and tetryl. It was this type of protective ointment that was successfully used by our Armed Forces as an "antiflash" ointment to protect gunners against backflash. Into this type of protective ointment or film, chemical light screens may be incorporated to protect against coal tar, pitch, and other photosensitizers. Some of the chemical light screens used in these creams are the salicylates, the benzoates, the anthranilates, the tannates, the cinnamates, cycloform, and aesculin.

Most of the protective creams, emulsions, and lotions on the market can be classed under one of the above types of protective ointments.

VII. Treatment

Most cases of industrial dermatoses occur among new employees, and they are usually mild in character. Such persons, in addition to mild symptomatic treatment, should be given a suitable protective ointment to apply to the exposed parts and suitable protective clothing (impervious gloves, aprons, sleeves, coveralls, etc.), and should be kept on the job. Most of them will get well while working and will become "hardened." Those who do not should be given other work where they will not come in contact with the irritant.

In applying medication to acute lesions, only the mildest forms of lotions or ointments should be used. Calamine lotion, aluminum acetate solution 1–200, and boric acid solution 1–100 are examples of soothing evaporating lotions. When the acute symptoms have passed, mild ointments are to be used. Such ointments are boric-acid ointment, zinc-oxide ointment, Lassar's paste, calamine ointment, etc.

Recently, lotions and ointments containing Hydrocortone, Cortisone, Prednisolone, and ACTH have been found by some investigators to be of value in the treatment of acute occupational dermatitis. Ointments containing the antihistaminics are said to be of value also, especially in allergic dermatoses.

Strong medicaments containing antiseptics and antibiotics are contraindicated because contact dermatitis is at first a chemical irritation. When the presence of pyogenic organisms complicates the chemical dermatitis, such antiseptics and antibiotics may be used.

Chemical burns, when received, should be immediately immersed in water or flushed with water to dilute or remove the irritant and then treated as any other burn. In some factories where there is a hazard from chemical burns, shower baths are placed at strategic points so that if a strong acid or alkali splashes the worker he can immediately step under a shower bath, fully clothed, and wash away the irritant. In other factories where there is a hazard from localized alkali burns, for instance, in viscose manufacture, a weak solution of acetic acid is kept handy in a bottle so that it can be applied immediately to the places where the alkali has touched the skin. In factories where there is danger of acid splashes, bottles of a solution of sodium carbonate or of limewater are kept handy to apply to the site splashed by the acid. It is doubtful whether such practices are better than or even equal to flushing with plenty of water.

Ulcers resulting from such corrosives as chromic acids and chromates, zinc chloride, and fluorides are best treated by thorough curettement of the base, followed by aseptic dressings. Injections of calcium gluconate below the ulcers were, at one time, advocated by some dermatologists, but in the hands of the author they have proved to be of no value.

No general rules can be given for the treatment of the chronic eczematoid or chronic lichenified types of dermatitis. The treatment is left to the judgment of the dermatologist and depends on the stage and extent of the lesions, the complications present, and the condition of the patient.

VIII. Occupational Cancer

Workers exposed to soot, pitch, coal tar, crude petroleum from certain localities (such as Scotch shale oil), x-rays, radium, and excessive solar radiation have a high rate of skin cancers. Chromic acid and chromates have been found to cause lung cancer.

A. SOURCES OF OCCUPATIONAL CANCER

Soot. Cancer of the scrotum among chimney sweeps was reported in England as eight times more prevalent than among the general population. It is caused by rubbing the soot into the scrotum as the sweep is squeezed when descending the chimney. It is practically nonexistent in other countries and is on the decline in England.

Coal tar. The heavy coal-tar distillates and pitch are the most frequent causes of occupational cancer. In the United States more than 90 per cent of all reported occupational cancers are caused by coal tar and its heavy distillates. The rate of skin cancers among workers with coal-tar pitch is high; the author found 5 cases among 100 workers. Tar and pitch from gas works are more carcinogenic than tar and pitch from coke ovens. Road builders, roofers, conduit makers, and briquet makers are some of the workers outside coal-tar and gas plants who handle coal-tar products and are often affected with skin cancers.

Petroleum. Workers in petroleum fields, especially where the crude oil is highly carcinogenic, are subject to occupational skin cancers. Shale-oil workers are said to have a carcinoma incidence of 1 per cent annually. Pure medicinal petroleum oils are not carcinogenic. Treatment with sulfuric acid during the refining process destroys the cancer-producing principle. Mule spinner's cancer of the scrotum has not been observed to be caused by spindle oils of American origin. It has been reported in England and is caused by friction of the oil-soaked clothes against the scrotum of workers on mule spinning machines which throw an oil spray. It can be prevented by wearing oilproof aprons.

Aniline. Workers in factories making synthetic dyes and exposed to benzidine, α-naphthylamine, and β-naphthylamine, have a high rate of papillomata and carcinoma of the bladder.

Chromium. Workers engaged in the manufacture of chromium salts and chromic acid have been found to have a large excess over the normal incidence of lung cancer.

X-rays. X-ray technicians and tube makers have a comparatively high rate of occupational cancer.

Radium. Radiologists, workers with radium, have a high incidence of occupational cancer. Radium dial painters have developed malignant bone tumors from the ingestion or inhalation of radium. Cancer of the lungs is prevalent among miners of radium ore. Uranium miners cancer has not yet been reported.

Actinic rays. Outdoor workers, such as fishermen, sailors, soldiers, and farmers, have a high incidence of skin cancers.

Trauma. Malignant tumors may develop at the site of chemical burns and repeated traumatism. That a single trauma can cause cancer is debatable and is difficult if not impossible to prove. In order to prove it, it must be shown that the part was normal before the trauma; that the trauma was at the site of the cancer; that a sufficient interval elapsed between the trauma and the appearance of the cancer; that there was no other traumatism at the site of the cancer during this interval; and biopsy must verify the malignant nature of the growth.

Heat. Cancers can arise in cicatrices of burns, usually a number of years after the burn.

B. PREVENTION OF OCCUPATIONAL CANCER

Workers having keratoses, warts, or xeroderma should not be employed in occupations where there is a marked cancer hazard. Processes giving off tar or pitch fumes should be enclosed. Persons working with carcinogenic coal-tar derivatives should be furnished with clean work clothes daily and be compelled to take showers after work. Protective ointments containing chemical or physical light screens are useful to protect against excessive sunlight.

IX. Methods of Investigation

In order to investigate intelligently the cause of occupational dermatoses, one must have at least a sufficient knowledge of dermatology to distinguish contact dermatitis from such ordinary nonoccupational skin diseases as psoriasis, impetigo, urticaria, and pityriasis rosea. In addition, one should have a fair knowledge of the action of industrial chemicals on the skin. The actual investigations in factories will give one the knowledge of industrial processes that is another essential requirement.

Before one can hope for success in finding the cause of a particular outbreak of occupational dermatitis, it is necessary to have the experience and knowledge gained by studies of the skin hazards and the normal incidence of occupational dermatoses in the basic industries. Such studies not only acquaint one with the irritating properties of various chemicals, but often lead to the discovery of health hazards not previously reported. The basic industries should be selected for routine studies because they manufacture the chemicals used in all other factories, and their workmen are subject to the hazards of contact with these chemicals.

The first step in an investigation is to discuss with the plant superintendent the occupational diseases, especially those of the skin, that to his knowledge have occurred in the factory, and to obtain from him lists of the raw materials used in the factory and of the products manufactured. The next step is to consult with the plant physician, if there is one, or with the nurse or first-aid attendant, concerning the chief infections or diseases treated in the dispensary, and to obtain from them a little better conception of the incidence of skin diseases than was obtained, perhaps, from the superintendent. The medical records, if any have been kept, are then examined regarding the number of cases of skin lesions treated, the causes given for their occurrence, and the departments in which the patients worked. This procedure often yields a clue as to what part of the factory has the greatest skin hazards. It is also well at this time to request that those of the workers who have had occupational skin diseases or who are known to be affected at the time be called into the dispensary to be questioned and examined. This makes it possible to check and evaluate the criteria used by the plant physician in making a diagnosis of occupational dermatitis.

The superintendent is then asked to appoint someone familiar with all the industrial processes in the factory to escort the investigator through the plant. He may begin at the point where the raw materials come in and follow them through the plant until the finished product is ready for shipment. In each department visited, first interview the foreman, asking him if he knows of any workers who have now or ever have had skin diseases, and what in his opinion caused these diseases. Then go through the department and have the manufacturing process explained. Examine the hands and faces of the workers for skin lesions, at the same time taking note of their work clothes, whether they are clean or dirty, and whether protective clothing in the form of gloves, aprons, boots, respirators, and so forth is worn; note the cleanliness of the workroom, and whether there are any safeguards on the apparatus, such as ventilating hoods; and ask each worker if he now has or ever has had any skin diseases. The names of workers who are found to be affected with skin lesions or who state that they have been affected at some time or other are taken, and at the end of the day's inspection these workers are summoned to the dispensary and examined further.

The primary inspection of the men at work takes but a short time—not over a half minute for each man. The same procedure is followed in every department, and notes concerning the industrial processes and hazards are taken. At the end of the day's inspection, usually an hour or so before the end of the day's shift, go to the first-aid room and send for the workers found during the inspection to be affected with skin diseases. Such workers are examined one at a time with only the plant physician, nurse, or first-aid attendant present. The worker is required to disrobe completely and his body is examined for the presence of skin diseases. It is important to strip the patient because often an important clue to the diagnosis is revealed that might otherwise be missed.

A card record is made of the patient, including the name, sex, age, color, and a detailed description of the worker's occupation and the chemicals with which he comes in contact. The date of entering his present occupation is noted, as is also a history of his previous occupations. A record is made of previous skin diseases and of any allergic history; a detailed account of the present skin diseases is taken, with the date of onset and the symptoms noted down; a written description of skin lesions and their location is made on the card; the patch tests, if any are performed, are also described, the names of the chemicals applied as patches, the length of time they are allowed to remain on the skin, and the resultant reactions being given. Based on these data the diagnosis is made and the actual skin irritant, if found, is named. Under the heading "Remarks" complicating skin lesions and treatments are recorded.

When a number of factories manufacturing the same products have been examined, a fair idea of skin hazards in that particular industry is obtained. The knowledge and experience gained by routine studies of industrial processes and skin hazards in basic industries prepare one to undertake intelligently the investigation of the causes of outbreaks of occupational dermatoses. The requests for such investigations come from insurance companies, the management of factories, and labor unions. Such outbreaks of occupational dermatoses usually occur when new chemicals are introduced, or when new manufacturing processes are being installed, or when there is some change made in old manufacturing processes.

While outbreaks of occupational dermatoses usually occur in only one department of a factory, it is necessary to study not only that one department, but the whole process of manufacture. Sickness records of the plant for at least a year previous to the outbreak should be studied in order to determine whether the outbreak occurred suddenly, or whether there was a gradual increase in the number of cases of dermatitis; and whether there was any connection between a sudden increase in the incidence and the use of new chemicals, new processes, or changes in old processes in the factory. Detailed inquiries should be made of the superintendent, the foreman, and the workers as to changes in manufacturing processes and the introduction of new chemicals preceding the outbreak of dermatitis.

Patch tests should be performed with all the allergenic materials handled by the affected workers, in an effort to track down the offending substance. In some instances the management purchases, under trade names from other concerns, the chemicals used, and does not know their composition. It is necessary in these cases to trace the chemicals to their original source of manufacture and determine what they really are.

X. Skin Hazards According to Types of Workers or Occupations

Abattoir workers and butchers may contract anthrax and erysipeloid from infected animals. Those employed to clean intestines sometimes suffer from "hog itch," a dermatitis of the hands and forearms caused by allergy to the secretions of round worms in the hog's intestines. Glanders and actinomycosis are rare, but may occur. Butcher's pemphigus is also a rarity. Verruca necrogenica is not uncommon. Butchers and abattoir workers should immediately disinfect all abrasions and cuts. They should not scratch any part of the body without disinfecting the hands. Those engaged in cleaning entrails should wear long rubber gauntlets.

Agricultural workers may develop skin cancers from excessive exposure to sunlight. They may contract dermatitis from poisonous plants. Parasites of grain and straw may attack the skin. Ground itch (hookworm) may be contracted if shoes are not worn. Cowpox, sheep pox (ovinia), and sheep thrush may be contracted from infected animals. Agricultural workers should protect themselves against excessive sunlight. They should immediately disinfect all abrasions and cuts and wear gloves when likely to be exposed to poisonous plants.

Airplane workers may develop dermatitis from (*1*) protective coatings on duralumin, (*2*) solvents in "dopes" and paints, (*3*) cutting oils, (*4*) woods, such as mahogany, (*5*) glues, (*6*) strong caustic cleansers, (*7*) electroplating operations. Prevention consists in protective clothing against solvents, oils, and caustics, and frequent washing to remove glues.

Asphalt and pitch workers are particularly subject to comedones, acne-like lesions, keratoses, epithelioma, melanosis, and photosensitivity. To prevent these they should have a daily change of clean work clothes, take cleansing showers after work, and use a protective ointment containing physical and chemical light screens.

Bakers and millers are subject to allergic eczemas from flour and the conditioners and bleaches contained therein. Sometimes bakers develop a sensitivity to flavoring agents, such as cinnamon and vanilla. The daily change to clean work clothes, and the wearing of rubber gloves are preventives.

Bricklayers, cement workers, and masons are subject to dermatitis from lime, cement, and paint. Cleansing showers after work, daily changes to clean work clothes, wearing of dustproof coveralls, use of protective ointments on the face, and wearing of rubber gloves are the preventive measures.

Cabinetmakers and carpenters use solvents and thinners in varnishes and lacquers that are chief causes of dermatitis. The resins, both natural and synthetic, used in varnishes, lacquers, and glues also affect some workers. Poisonous woods, cocobola, embuia nectandra, swietenia macrophylla, and others, may cause allergic dermatitis. Preventive measures consist of daily changes to clean work clothes, cleansing showers after work, protective ointments, and rubber gloves.

Candy makers may become sensitive to the materials used for flavoring, such as cinnamon and vanilla; they may develop dermatitis and paronychia from fruit juices and sugar. Prevention consists of personal cleanliness and wearing of rubber gloves.

Canning of fruit and vegetables. Dermatitis is fairly common among all handlers of fruits and vegetables; the juices containing sugar, acids, and essential oils and the alkalies used for cleaning and peeling may cause dermatitis and paronychia. Monilia infections of the interdigital spaces and around the nails are not infrequent. Those handling citrus fruits, peaches, tomatoes, carrots, and asparagus are especially prone to dermatitis. An enzyme in pineapples can cause dermatitis. Prevention consists of the wearing of rubber gloves with impervious sleeves fastened over the gloves at the wrists and impervious aprons, and personal cleanliness. Applying equal parts of lanolin and cold cream to the hands at night aids in prevention of dermatitis.

Dyeing. The strongly alkaline vat-dye liquors and the strong acid-dye liquors are more frequently the cause of dermatitis than are the dyes themselves. The mordants, especially the alkaline dichromates, often cause dermatitis. The strong scouring soaps and bleaches used on the fabrics before dyeing often cause dermatitis, as do the volatile solvents used to remove spots from the dyed fabrics. Preventive measures consist in wearing rubber gloves, impervious sleeves and aprons, and rubber boots when working on wet floors, and personal cleanliness.

Dye manufacture. Workers in this industry are exposed to strong organic and inorganic acids and alkalies as well as to intermediates, many of which are primary skin irritants and most of which are sensitizers. Most of the finished dyes are harmless but a few of them may cause dermatitis. Workers exposed to benzidine, α-naphthylamine and β-naphthylamine may develop papilloma of the bladder. Prevention of dermatitis consists in compulsory showers after work, daily change to clean work clothes, and wearing impervious sleeves, aprons, and gloves. Exhaust hoods over dusty and fume-evolving processes, or totally enclosed manufacturing processes, are necessary.

Electroplating. The acids, alkalies, and solvents used to clean the parts before plating and the irritant vapors of dichromates, cyanides, and others coming from the plating tanks, are skin irritants. Prevention consists in daily change to clean work clothes, wearing rubber gloves, impervious sleeves and aprons, using petroleum jelly in the nostrils to prevent nasal mucitis and protective ointments on the face, and exhaust ventilation over plating tanks.

Explosives manufacture. Workers exposed to tetryl, TNT, picric acid, and the picrates have the hair and hands discolored and may also develop dermatitis of the face and hands. Fulminate of mercury does not discolor the skin but does cause dermatitis. Ammonium nitrate, DNT, and Hexite also cause dermatitis, but not as frequently as tetryl and TNT. Prevention consists in daily change to clean work clothes, showers after work, wearing impervious gloves, using protective ointments on the face, and, for tetryl workers, petroleum jelly in the nostrils.

Felt hat manufacture. The "carrots" used on the furs (either mercuric nitrate or the alkali carrots) are skin irritants. The "starting solutions" are also skin irritants, as are the dichromates used in dyeing the fur. The "sizings" used to stiffen the felt may cause dermatitis. Prevention consists in wearing impervious sleeves, aprons, and boots when working on wet processes.

Fertilizer manufacture. Workers are exposed to the dust of nitrates, calcium cyanamide, fluorides, and other irritant chemicals. Bone dust irritates some workers. The solvents used to extract fat from animal refuse may cause dermatitis. Prevention consists in allaying of dust, use of exhaust hoods over dusty processes, daily change to clean work clothes, and showers after work.

Fishing industry. There are many skin hazards in the catching and handling of fish. Abrasions and lacerations from the bony spines of the fish and from the fishing gear are frequent. Secondary infections of such wounds are not at all uncommon. Chronic boils called "pidgeons" and erysipeloid are not unusual among secondary complications. Certain fish inflict bites and stings. Handlers of mackerel may develop dermatitis from "red feed," red-orange crustaceans on which the mackerel feed.

Florists are subject to many of the occupational diseases that affect agricultural workers. In addition to these, pricks, cuts, and scratches from thorns on flowers are not infrequent. Certain flowers and plants are well-known skin sensitizers. Certain bulbs, such as tulip, hyacinth, and narcissus, can cause eruptions on the hands and around the finger nails of those handling them. Sporotrichosis is occasionally reported among florists. The sporothrix enters the skin through a break. The organism may be transmitted by various plants, especially by the barberry shrub. Prevention consists of cleanliness and wearing rubber gloves.

Fluorescent light manufacture. In the manufacture of fluorescent lamps beryllium was at first used. Powders containing zinc beryllium silicate, zinc manganese beryllium silicate, and beryllium oxide constituted the chief hazard. There have been many cases of sarcoidlike lesions of the skin among the handlers of these powders. Cuts from beryllium-coated glass also have caused such sarcoids. Cases of chronic pulmonary berylliosis have been reported in this industry. The lesions in the lungs simulate pulmonary sarcoids. The use of beryllium in the fluorescent-lamp industry has practically been discontinued. Glass cuts should receive immediate medical attention.

Furriers may develop dermatitis from the chemicals used to preserve the pelts: salt, arsenic, and lime. Those engaged in "fleshing" suffer from loss of the nails. The mordants and tanning agents, such as dichromates, alum, and formaldehyde, may injure the skin. Aniline salt, aniline black, and paraphenylenediamine are the principal irritant fur dyes. Prevention consists in the wearing of rubber gloves, impervious sleeves and aprons, rubber boots, and clean work clothes.

Garage workers may develop dermatitis from gasoline and from the strong soaps used to clean cars. These soaps if used to clean the hands cause dermatitis. Folliculitis of the arms and the thighs occurs from exposure to oils and greases. Prevention consists in wearing impervious sleeves and aprons, daily change to clean work clothes, and showers after work.

Glass workers. Alkalies, such as lime and sodium carbonate, and arsenic cause dermatitis among "batch mixers." Etchers may develop dermatitis from hydrofluoric acid. Lesions of the lip and teeth occur among glass blowers. Prevention consists of daily change to clean dustproof work clothes, rubber gloves for etchers, petroleum jelly in nostrils for those exposed to alkalies and arsenic, and showers after work.

Hairdressers and beauticians may develop dermatitis from ammonium thioglycolate and alkalies used for waving or straightening hair; from resins used to keep the hair curled or straight; from alkalies and solvents used to manicure; from hair dyes, tonics, and perfumes. Mycotic and pus infections may be contracted. Prevention consists in washing the hands after handling each customer, wearing clean rubber gloves and impervious sleeves and aprons, anointing the hands with equal parts of lanolin and cold cream before retiring at night.

Insecticide makers and users. All insecticides are skin irritants. Workers making and using them should protect the skin by showers after work and imprevious clothing changed daily.

Iron and steel workers. Those engaged in front of furnaces suffer from heat rashes and telangiectases. Those mixing batches may get dermatitis from lime and chromium. The acids and alkalies used in "pickling" may cause dermatitis as do "drawing" compounds used in drawing wire. Nitrate, cyanide, and soda ash many cause dermatitis among "case hardeners." Lubricants and quenching and cutting oils may cause folliculitis and acne. Core and mold makers may develop dermatitis from the chemicals used in the sand. Prevention consists in showers after work, daily change to clean work clothes, canvas or leather gloves to handle steel or wire, rubber gloves for "picklers."

Laundry workers. Principal skin hazards are disinfectants, strong alkalies, soaps, bleaches, and solvents. Dermatitis may be contracted from irritant chemicals on soiled clothes. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons, and in rubbing equal parts of lanolin and cold cream into the hands before retiring at night.

Leather tanners. Those engaged in handling the fresh hides are subject to the action of lime into which the hides are immersed as well as to the preservatives used to preserve the hides. The chemicals used for removing the hair are lime and arsenic and sodium sulfides. All of these can cause ulcers and dermatitis. The tanning agents, both vegetable and chemical, such as sumac, dichromates, and synthetic tannins, may cause dermatitis. The dyes used on leather affect the skin of some workers. Anthrax may be contracted from infected hides. Prevention consists in showers after work, wearing impervious gloves, sleeves, and aprons, daily change to clean work clothes, and immediate disinfection of all cuts and abrasions.

Machinists. The chief skin hazard is from the cutting oils, especially the insoluble cutting oils. They cause folliculitis, acne, and pustules, and sometimes allergic eczemas. Metal chips may wound the skin. The solvents used for degreasing are also a prolific source of dermatitis. Alkaline coolants may defat the skin and cause dermatitis. Prevention consists in showers after work, daily change to clean work clothes, wearing impervious sleeves and aprons, protective ointment.

Painters. Most of the dermatitis among painters is caused by solvents and paint thinners and not by pigments and dyes used in the paint, although some persons may be allergic to these chemicals. Paint removers are all strong skin irritants, as are the wood preservatives such as arsenic, tar distillates, zinc chloride, and dichromates. Prevention consists in showers after work, daily change to clean clothing, impervious sleeves, aprons, and gloves.

Paper makers. The alkalies used in digesting wood pulp, the black and green liquors, the bleaching solutions, and the resins used for sizings are the principal skin irritants in paper manufacture. Prevention consists in personal cleanliness and impervious sleeves, gloves, aprons, and boots.

Petroleum field workers and refiners. Workers in the oil fields, especially pumpers, pipe pullers, and repairmen, are subject to folliculitis, acne, and keratotic lesions produced by crude petroleum. In torrid climates they are also subject to the keratoses and melanoses produced by the combination of the oil and actinic rays. The harsh cleansers used to remove oil and grease from the skin also may produce dermatitis.

In refineries the same hazards are present and in addition the crude paraffin waxes may cause acne, boils, and keratoses. Prevention consists in cleansing showers after work, daily change to clean work clothes, and the use of mild cleansers. Workers exposed to actinic rays should use ointments containing light screens.

Photoengravers and lithographers. The chief skin irritants are the alkaline dichromates used on the plates, the acids used in etching, and the photo developers. Solvents used for cleaning plates may cause dermatitis. Prevention consists in wearing long rubber gloves and impervious aprons when handling the irritant chemicals.

Photographers. The principal irritants are metol, used for photo developing, and dichromates, used for blueprint developing; pyrogallol, hydroquinone, silver sulfides, platinum, and mercury salts may also cause dermatitis. Prevention consists in wearing long rubber gloves and impervious aprons when working with the developing and fixing solutions.

Plywood workers. The principal skin hazards are the glues, especially those made of synthetic resins and those containing strong alkalies, such as the casein glues. Some workers may become sensitized to the woods. Personal cleanliness, daily change to clean work clothes, protective ointments on the face, and the wearing of washable light leather gloves are methods of prevention.

Printers. Solvents used to clean the presses are the principal skin irritants. Harsh soaps to remove dye from the skin also cause considerable dermatitis. Some persons may be allergic to dyes. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons when cleaning presses and using mild soaps and cleansers to remove inks from the hands.

Railroad workers. Railroads have employees on many different types of occupations in which there are skin hazards. Workers cleaning and disinfecting railroad cars are exposed to skin hazards from strong cleansers, from which they can contract dermatitis similar in appearance to housewive's eczema, and to disinfectants and insecticides, which also may irritate the skin. Workers laying or servicing railroad ties are exposed to dermatitis from wood preservatives, such as coal tar, creosote oil, and zinc chloride, with which the ties are treated. Such workers may have occupational tar acne, keratoses, and epitheliomata. Workers in machine shops are exposed to strong alkaline solutions used for degreasing machine parts, as well as to strong solvents used for the same purpose. Dermatitis among these workers is not infrequent from petroleum solvents, chlorinated hydrocarbon solvents, and stripper solutions. Workers on Diesel locomotives, in addition to the above hazards, also come in contact with the Diesel coolants, which may contain dichromates and sodium carbonate solutions as antirust compounds. As the Diesels are serviced, disassembled, and reassembled, it is possible to have contact with the coolants containing antirust compounds and develop eczematoid type of dermatitis. Dermatitis also can be caused by the Diesel fuel oil, which acts to degrease and irritate the skin much the same as do other low-boiling petroleum distillates. The principal methods of prevention of dermatitis among railroad workers are protective clothing, protective ointments, and cleanliness. Wash basins supplied with hot and cold water, industrial soap, and paper towels should be so placed in the roundhouses, machine shops, and yards that no worker need walk more than 100 feet in order to have access to them.

Rayon manufacture. Workers in contact with wood pulp treated with sodium hydroxide may develop dermatitis and ulcers. Those exposed to carbon disulfide may develop dermatitis and systemic poisoning. Workers at the precipitating baths are exposed to alkali viscose coming from the spinnerettes as well as to sulfuric acid in the baths. The bleaches used on the rayon are skin irritants. The preserving solutions in which cellulose caps are immersed for storage are skin irritants. Workers spinning and coning rayon thread may develop allergic dermatitis from the ingredients in the coning oils. Makers of acetate rayon are exposed to acetic acid and acetone and those making cellulose nitrate are exposed to nitric and sulfuric acids as well as solvents. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons and changing daily to clean work clothes.

Resin manufacture. Workers exposed to phenols, aldehydes, urea, and the monomers of polymerized resins may develop dermatitis from these chemicals. Hexamethylenetetramine used in some of these resins also causes dermatitis. Prevention consists in daily change to clean work clothes, showers after work, impervious sleeves, aprons, and gloves, and protective ointment on the face where dust and fumes cannot be exhausted. Incompletely cured epoxy resins cause dermatitis.

Restaurant workers. Soaps and other alkali cleaners cause dermatitis among dishwashers. Mycotic infection of the nails is an occupational disease of dishwashers and soda-fountain attendants. Fruit and vegetable juices may cause dermatitis. Prevention consists in wearing rubber gloves, impervious sleeves, and aprons; using mild cleansers for the skin; and applying lanolin to the hands before retiring.

Road makers. Workers are exposed to the action of actinic rays, tar, and asphalt, which may cause melanosis, cancer, photosensitivity, acne, and folliculitis.

Prevention consists in showers after work, daily change to clean work clothes, and protection against the sun.

Rubber manufacture. The chief irritants are the accelerators, antioxidants, and other chemicals going into the manufacture of rubber, the sulfur chloride used for "vapor curing," and solvents used to make rubber cements. In reclaiming rubber, alkalies are the chief skin irritants. In the manufacture of synthetic rubber, dermatitis may occur not only from the above-named chemicals, but also from styrene, acrylonitrile, and other chemicals used. Prevention consists in showers after work, clean dustproof work clothes daily, and protective ointments on the face to protect from dusts and fumes.

Ship builders. Welders are subject to flash burns (*see welders*) and electricians handling cables are subject to acne (see *wax makers*).

Solderers. Hydrochloric acid fumes and zinc chloride may cause dermatitis. Prevention consists in wearing impervious sleeves and applying protective ointment to the face.

Sugar refiners. Hot solutions of sugar crystallize on the skin and enmesh the hairs; boils may result when crystals are pulled off and hairs are pulled out. Paronychia may occur, and also dermatitis from alkalies used to purify sugar and from the dehydrating action of sugar. Prevention consists in daily change to clean work clothes, impervious sleeves, gloves to handle dry sugar.

Varnishers and lacquerers. The resins are skin irritants as are the solvents and thinners; the dyes and pigments are only rarely so. Prevention consists in daily change to clean work clothes, rubber gloves, and impervious sleeves.

Wax makers (synthetic). Solid chlorinated hydrocarbons cause acne-like lesions. Prevention consists in showers after work, daily change to clean work clothes, and proper exhaust ventilation.

Welders (and helpers). Flash burns may cause dermatitis, melanosis, and "eye flash." Dermatitis occurs from fumes of irritant metals contained in alloy steels. There is danger of spark burns. Prevention consists in wearing proper masks and dark glasses and flameproof clothing.

CHAPTER XV

The Visible Marks of Occupation and Occupational Diseases

CAREY P. McCORD, M.D.

I. Introduction

Some, but not all, trades lead to external markings or signs on workers that may serve to identify either the trade or the diseases associated with the trade. In times past the term "stigmata" has been widely applied to these marks, but this term is at times inappropriate and confusing. In medicine, "stigma" or "stigmata" has been chiefly limited to the skin, and often possesses religious connotation. In general, the term denotes disgrace or inferiority. This is far removed from the purposes of a manifest of the signs of various trades imprinted upon the worker, many of which constitute honorable badges of long years of service. For this reason the designation "stigmata" is carefully avoided in relation to occupation. As here presented, the markings of trades and trade diseases are limited to those evidences that may be seen by the layman as he may observe attired human beings at the factory entryway or on a bus or train, or as he passes along the aisle of a work department. The term "layman" in this instance merely indicates that the observer is not a physician, a nurse, or a dentist; he might well be highly skilled as an engineer, a chemist, or lawyer. Frequently the signs that may be observed are not single but occur in groups to which the term "syndrome" is well applied. Thus, given a known exposure to manganese, anyone presenting an expressionless, masklike face, who is unable to purse the lips as in whistling, whose gait is apparently not quite controlled, and who indulges in fits of unprovoked laughter or crying, should be suspected of having manganese poisoning. These signs constitute the syndrome of that disease.

While some definite medical ends may be served by a knowledge of occupational signs in their hundreds of variations, greater interest may reside in intellectual curiosity about the tell-tale indications of different trades or different trade diseases as branded onto the bodies of those who ply them. On the street, or anywhere else, there might be observed a man who reveals a circular hole about the size of a dime in the midline of his teeth as they rest in apposition. Further, it might be noted that this individual is having some difficulty with his breathing, the inhalations being feeble and short while the exhalations are prolonged and possibly labored. The astute observer at once will realize that he is in the presence of an old-time glass blower with emphysema—the characteristic occupational disease of that trade. The unfavorable critic may urge that such is not the case, that the observed individual is merely an aged pipe smoker with asthma. But there is a difference. The pipe smoker's dental hole is smaller, more likely to be oval and, moreover, to be right or left of the midline. Other signs may reveal not especially the trade, but a specific occupational affection. Let it be assumed that a stranger unexpectedly enters a workroom, whereupon the workers therein immediately appear to be frozen in whatever position exists at the moment. An entire group of workers on such an occasion may resemble a grotesque lot of statues—utterly embarrassed, incapable of motion, little capable of speech. To the knowing one, these signs at once should suggest the erethismus of mercury poisoning. One of the classical stories about mercurial erethismus centers about a group of hat makers with nondisabling mercury poisoning who were gathered together after work in a saloon for drinking purposes when a stranger entered. During the entire time the unfamiliar person remained, not one of these hat makers was able to lift a glass to his lips or to make other movements—because of pathologic shyness and timidity.

There is no intention here to suggest that all occupational diseases present obvious outward evidences of their existence so that he who runs through a factory may make precise diagnoses. More often than not, when a disease state has reached the point of gross, external characteristics, the time has long passed at which the condition should have been recognized. It is equally obvious that many visible marks are related to nonoccupational diseases and injuries. It is nonetheless true for nonmedical workers in industry, and significantly for the industrial hygienist, the safety engineer, the chemist, the foreman, and the superintendent, that a wide acquaintance with unusual markings on the body or in the actions of workers may serve an end helpful to all. Such workers should know that many drugs taken internally may lead to peculiar markings on the skin; thus, some laxatives containing phenolphthalein may, even when taken by the manufacturer's directions, produce pigmented skin blotches as large as those of the leopard. They should know that some diseases and some work materials may identify themselves in the breath of the person involved, even though this does not constitute a visible sign. They should know that some tradesmen may suggest their jobs through bodily markings or actions, for example, the dirt farmer by his bronzed, warty skin, the train dispatcher by his proneness to cock his right ear toward you because of partial deafness in the left. They should know that the evidences of some acute diseases may be found in the altered color of the skin, as the cherry red skin of the victim of carbon monoxide. They should know that from the gait of some workers some diseases may be spotted with precision, as in the case of some syphilitics who go about their duties with high, slapping steps like a prancing horse.

The unfavorable critic, with some justification, may claim that a mere familiarity with a large number of heterogeneous signs provides insufficient information for any practical application—that engineers, hygienists, chemists, and others may not be transformed into other than pseudo-physicians by the acquisition of miscellaneous lore about the external characteristics of diseases. Conceding part of the point, there still remain opportunities for the simple application of facts gained, as in the following instance.

Expansion in a small plant led to the employment of a number of young women for the first time and under somewhat unfavorable work conditions. Soon thereafter, more than half of the women developed what was for them an alarming livid eruption over their shins, roughly resembling a bluish-red Scotch plaid. No male worker, although in the same department, was afflicted. Sheer panic was in the making, claims and acrimony. Then came the safety engineer, not a physician, but experienced in the markings of some diseases. He simply pointed out that in that expanding department it has been necessary to introduce several coal stoves, and that the girls, being more thinly clad than the men, had stood or sat for long periods close to these hot stoves, with the resulting patchy lattice work corresponding to the distribution of the superficial blood vessels in these girl's lower legs. This common condition is known to the dermatologist as "erythema ab igne" —"skin redness from fire." This condition is familiar to every country boy and girl who goes barefoot late in the fall or early in the spring and hovers close by the open fireplace or stove. It is information of this character that provides ever-expanding opportunities for nonmedical personnel in industry.

Widely, characters in fact and fiction have become famous through infinite capacity to observe and interpret apparently trivial external markings on the human body. In no small part, the fame of Osler, America's greatest contribution to medicine, rests upon this ability, while in fiction Sherlock Holmes, as created by another physician, gained part of his immortality through this same quality of genius. However, there is nothing so sacred in the domain of medicine as to bar nonmedical personnel in industry from observing physical peculiarities of workers, and setting in motion appropriate steps that may lead to helpful interpretation.

II. Stigmata of Degeneration

In an earlier period, and chiefly among criminologists, a vogue long existed centering about numerous anatomic or physiologic deviations from the usual in relation to criminals, perverts, the insane, the epileptic, the feeble-minded, and the degenerate. These deviations were termed "stigmata of degeneration," and this term designedly indicated inferiority or disgrace. It was thought that the unfortunate possessors of such abnormalities as supernumerary fingers, webbed toes, pointed ears, or microcephalic (small) heads might in the over-all picture be more frequently encountered in the undesirable citizenry than elsewhere. While in feeble-minded, insane, or penal institutions there may be found a greater number of divers stigmata of degeneration, it does not follow in every instance that these markings are significant. In a court trial, some stigmata of degeneration might as often be found on the prosecuting attorney, the judge, the doctor in the witness chair, as on the prisoner at the bar. Inevitably, many of these stigmata of degeneration will be exhibited by industrial workers and be wholly unrelated to occupational signs. Since so many unhappy interpretations of these congenital or hereditary markings are made, it may be desirable, even on a negative basis or basis of sympathetic understanding, that some of these so-called degenerative signs here be included.

The most obvious stigmata of degeneration are anatomic. On a lower level of discernibility are physiologic and physical signs. On an anatomic basis, almost any organ, system, or portion of the body may be involved, or even the body as a whole. Thus, there may be decidedly large, small, elongated, or asymmetric heads. Common are deformities of the palate, best observed as "harelip." Quite apart from dental anomalies associated with work causes, there may arise congenital dental defects. Tongues may be excessively large, small, or bound down. In the eyes at birth there may exist cataracts; the two eyes may be of wholly different color; the eyes may be crossed (strabismus). Occasionally, eyes may be pathologically small. Unusual closeness of the eyes one to another is sometimes regarded as a sign of degeneration. A number of stigmata are associated with the ears, and perhaps without great significance, such as: the implantation of ears at different levels, excessive length of ears, the absence of one or both ears, very small ears, the binding down of the lobule to the neck, the congenitally thickened or knobbed ear, which is in distinction to the "cauliflower ear" of the boxer, ears that are implanted too far forward or too far rearward, the ear without external auditory canal, etc.

In the realm of stigmata of limbs, there may be mentioned: excessive numbers of fingers or toes, varying degrees of webbing of fingers or toes, the absence of one or more fingers or toes, improper location of fingers or toes, excessive length or shortness of entire limbs or portion of limbs, such as in achondroplasia (one form of dwarfism). In addition, many stigmata are seen in such instances as the clubfoot, entire absence of certain muscles or muscle groups, or the absence of certain joints.

A wide variety of congenital peculiarities of the skin may be classed in the category of degeneration. A few of these are the absence or scantiness of hair, the occurrence of hair in unusual places, unusual colors of the skin, albinism, absence of nails, ichthyosis (fish scale skin), congenital tumors, and so on.

Some deviations from the normal affect the body as a whole, such as: dwarfism, gigantism, infantilism, femininism, masculinism, certain types of obesity, progeria (childhood characterized by premature senility), mongolism (one form of physical and mental defection characterized by physical resemblance to Mongol races), and so forth.

In like manner, anatomic stigmata of degeneration by the hundreds have been associated with every other portion of the body, including the lips, nose, neck, chest, spinal column, and glands. In order that these anatomic defects may not appear too far afield from the practical, let it be pointed out that with few exceptions all inguinal hernias represent congenital defects, constituting in the majority of instances failure of complete anatomic structure in the inguinal area. Further, lest there be prideful feeling of freedom from the stigma of defects, let it be pointed out that every woman or man whose beauty or handsomeness partly depends upon winsome or seductive dimples is merely presenting minor anatomic defects. All persons possess some anatomic defects, and only when the number is large or the condition profound should much significance be attached to them as evincing degeneration. It is not remarkable that the mythologies of primitive people should center about some of the severer malformations of bodies. Thus, Janus undoubtedly had his counterpart in some actual human born with two faces. Medusa probably is to be associated with some woman afflicted with numerous horny growths of the scalp. The legendary mermaid finds basis in those rare cases of sympus or sirenomelus, a gross malformation in which the two lower extremities are fused. In more modern times and reminiscent of the side show, gross stigmata of degeneration are exhibited as the "turtle boy," the "dog-faced woman," the "bearded lady," and so forth.

The stigmata of degeneration on a physiologic basis are not so numerous, or at least not so obvious, though many compel attention. Likewise, physiologic deficiencies on a hereditary or congenital basis are not so readily separated as the anatomic ones from those caused during postnatal life. Again it may be pointed out that physiologic stigmata of degeneration may involve any portion of the body. Representative examples are: color blindness, some deafness, mutism, stuttering, blindness, constricted visual field, migraine, anesthesia, hyperesthesia, astigmatism, epilepsy, endocrine dysfunction (abnormal function), colored sweat, hyperodorous sweat, vicarious menstruation, dysfunction of appetite, and delayed puberty. Many instances of such conditions as deafness and blindness in no sense represent stigmata of degeneration.

In the psychic province there are unfortunately almost unlimited evidences of degeneration. These embrace some, but not all, feeble-mindedness, idiocy, imbecility, insanity, precocity, eccentricities, sexual perversions, and so on. Even genius itself, when warped, may be a sign more of degeneration than of exceptional brilliance.

The practical man at this point may be disposed to disavow any connection between the foregoing and the day-by-day world of medicine and industrial hygiene. This attitude is unwarranted. Many hundreds of thousands of workers go about their tasks with continuous mental, if not physical, discomfiture as a consequence of the departure from the usual found in their bodies, their physiologic functions, or their minds. They are in need of human understanding, of medical guidance. After all, industrial medicine is not limited to lead poisoning, silicosis, and broken bones.

III. Marks from Work and Work Diseases

Manifestly, occupational markings on the body are not the stigmata of degeneration in the above sense. Almost equally manifest is the fact that work signs are directly acquired and are not congenital; yet this statement is not precisely true, since some occupational affections of one or both parents may adversely influence the offspring. Hence, some children may present stigmata of degeneration when one or the other of the parents has suffered from such afflictions as lead, radium, or phosphorus poisoning. These and other materials constitute race poisoning and may, in fact, contribute to the degeneration of offspring.

As under foregoing circumstances, work marks, as observed in those portions of the body of an attired person that may be seen with the eye, may involve any external portion of the body, such as the skin and its appendages, the eyes, ears, nose, teeth, lips, limbs, and bones. Other signs may derive from posture, gait, mannerisms, or facial expressions. A number of more common ones such as should challenge the attention of nonmedical persons are listed on pages 486–510. For the purpose of differentiation between occupational and nonoccupational afflictions, some nonoccupational affection signs are included. R. M. I. represents "Recommended Medical Investigation."

IV. Summary

In cursory fashion, numerous signs of disease and near-disease states directly or indirectly related to work are presented in terms designed for nonmedical personnel.[1] Never will any listing of occupational and disease stigmata be complete. New items continually are appearing. By iteration it is observed that the objective here is to take notice of physical peculiarities that readily attract the curiosity of the layman and at times provoke apprehension lest there exist some state of communicability. Conversely, the point of view is not that of the physician making more nearly exact observations, interpretation, and ultimate diagnoses. Most occupational dermatoses and callosities are far from characteristic of any one or few trades and thus are not revealing. However, a callosity (for example) that characteristically appears on just one or two fingers would possess identifying values and thereby justify inclusion here. Always the emphasis is on the striking as observable through the eyes of the layman. The purpose has been twofold: (*1*) the hope of piquing the interest of nonmedical personnel in medical matters, and (*2*) the hope of bringing to the attention of physicians larger numbers of persons at workplaces genuinely in need of medical care.

In a measure all of this material fits into the precepts of the remarkable

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[1] For more extensive and technical medical data, reference is made to: W. E. and H. F. Robertson, *Diagnostic Signs, Reflexes and Syndromes*, 2nd rev. ed., Davis, Philadelphia, 1942. W. M. Barton and W. M. Yater, *Symptom Diagnosis*, 4th ed., Appleton-Century, New York, 1942. F. Ronchese, *Occupational Marks and Other Physical Signs*, Grune and Stratton, New York, 1948.

Dr. Joseph Bell who wrote: "Nearly every handicraft writes its sign-manual on the hands. The scars of the miner differ from those of the quarryman. The carpenter's callosities are not those of the mason. . . . The soldier and sailor differ in gait. Accent helps you to district and, to an educated ear, almost to county. . . . With a woman, especially, the observant doctor can often tell what part of her body she is going to talk about."

V. Common External Marks of Occupation or Occupational Diseases or Other Diseases

Mark or sign	Probable cause	Significance	Comment
		Skin	
Pallor—transient (white skin).	Temporary blanching from fainting, fear, pain, nausea, loss of blood, shock.	Dependent on cause.	Not necessarily occupational.
Pallor—persistent (white skin).	Anemia from any of many causes.	R. M. I.	Many specific types of anemia related to work, such as "baker's anemia."
Pallor—localized (white skin).	Hysteria, freezing, pressure, localized poisoning such as from insect stings.	R. M. I.	More common among women.
Abnormal color (cherry red skin).	Carbon monoxide.	May be absent in carbon monoxide poisoning. More likely to involve ears, cheeks, lips, finger tips; instead of cherry red, carbon monoxide color may be yellowish red, greenish red, bluish red. R. M. I.	Patient usually prostrate.
Abnormal color (slatish purple skin).	Silver.	Condition of argyria; may be uniform, may be patchy. Color not always same in different cases.	Not always occupational; must have been exposed to silver; essentially incurable; not disabling.
Abnormal color (slatish violet, red splotches on skin).	Phenolphthalein.	Skin damage from laxatives containing phenolphthalein; splotches usually on arms and chest; may be one or a score; variable sizes; persistent; no superficial skin rash.	Sometimes leads to compensation claims. Unwarranted except in phenolphthalein workers.
Abnormal color (bluish purple skin).	Methemoglobinemia.	Distribution may be limited to ears, lips, fingertips, or possibly generalized. R. M. I.	May be associated with other forms of abnormal hemoglobin, such as sulfhemoglobin.
Abnormal color (bluish purple) Cyanosis	Heart disease.	Resembles preceding item as to color, but not cause; common manifestation of cardiovascular disease. R. M. I.	Ordinarily not occupational.

Abnormal color (yellow jaundice icterus).	Bile in skin; many causes of jaundice, including occupational causes, catarrh, cancer.	Depends upon exact cause, such as carbon tetrachloride. R. M. I.	In the young, commonly catarrhal; in the middle aged, usually gall bladder disease; in the old, usually cancer.
Abnormal color (bronze).	Many causes, such as suprarenal disease, arsenic, pellagra.	May be universal, diffused, or localized. R. M. I.	Important if extensive and persistent.
Abnormal color (coffee color).	Endocarditis.	May resemble Addison's disease or nicotinic acid deficiency except for distribution of latter. R. M. I.	Unrelated to work as cause.
Abnormal color (yellow). Carotinoid.	From the eating of excessive quantities of carrots, squash, oranges.	Harmless; rapidly disappears on correcting diet; resembles jaundice.	Most often found on palms and soles and around nose; unlike jaundice, does not involve eyes.
Abnormal color (yellow). Picric acid.	Picric acid and picrates.	Usually limited to point of contact.	May be associated with dermatitis; some picrates used in the treatment of burns may both discolor skin and induce dermatitis.
Abnormal color (orange). Tetryl.	Munition materials.	Discolored area limited to contact points; may be associated with dermatitis.	Sometimes removed by washing.
Abnormal color (green).	Either from sweat from copper content, or external contact with fine copper.	Clinically not important; at times may be washed away.	Hair may turn either green or blue; disturbing to workers, particularly women.
Abnormal color (bluish-green streak or blotches).	Powder burns or ground-in coal dust; usually limited to miners, and chiefly coal miners.	Not ordinarily disabling, although previous injury may have been disabling.	May resemble chlorosis in appearance.
Abnormal color (hectic flushed cheeks).	Heart disease or tuberculosis.	Represents localized capillary dilatation.	In tuberculosis occurs only in far advanced state. More discernible in men.
Abnormal color (red skin).	Impending sunstroke, high blood pressure; may be natural for some types or races.	R. M. I.	May indicate fever; may be localized as on head, cheeks, or hands.
Abnormal color (leucoderma).	May be caused by external contact with certain rubber antioxidants. Monobenzyl ether of hydroquinone.	Frequently from nonoccupational causes; vitiligo; may be related to avitaminoses.	More prominent in Negroes and other dark races; loss of pigment fairly readily spontaneously replaced in some conditions.
Abnormal color (absence of normal skin sheen in Negro).	May be caused by any organic disease.	In reflected light, normal skin sheen almost invariably present in absence of organic disease.	A possible test for malingering in the Negro.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Skin, *continued*		
Abnormal color (excess pigmentation).	May be due solely to sunburn; some industrial causes, including superficial infection; nicotinic acid deficiency.	May be localized, spotty, or generalized; growing pigmented moles dangerous. R. M. I.	All marked hyperpigmentation without obvious cause should be investigated; characteristic of many trades, such as sailors. Bismuth, mercury, and arsenic used for therapy may induce excess pigmentation; also some cologne waters.
Abnormal color (any color—industrial tattooing).	Mechanical imbedding of fine materials; any color.	Usually limited to small areas. Equivalent of tattooing; not disabling.	Frequently associated with some scarring.
Abnormal color (any color).	Scores of chemicals directly color the skin, such as silver nitrate.	External contact with many types of work. Materials discolor skin with or without producing dermatitis, such as materials of photographers.	Such skin coloration frequently only identifies the trade, but may be associated with dermatitis.
Abnormal color (chocolate pigmentation with hyperkeratosis).	Possibly hydrocarbon oils, greases, or tars.	May involve forehead, sides of face, backs of hands, extensor surfaces of forearm, axillary folds.	Pruritus common. May represent Riehl's occupational melanosis.
Abnormal color (bronze deposits).	May follow use of iron compounds in treatment of dermatitis such as that from poison ivy.	Deposits sometimes disappear after long periods.	Ultraviolet application sometimes causes disappearance as does cantharides blister.
Abnormal color (blue nevi).	Unknown.	No more prone to become malignant than other nevi.	When any nevus changes in character, such as size or color. R. M. I.
Abnormal color (Berlocque pigmentation).	Sunlight exposure after some colognes, perfumes, or lotions.	Chiefly in summer in connection with bathing or sun bathing.	Involvement only of exposed part. Acute dermatitis sometimes present. Related to oil of bergamot.
Abnormal color (orange, through brown to blue-black).	Benzanthrone.	Common site face, neck, upper part of chest, sometimes hands and forearms.	May result from specific liver damage.
Rashes (misc.). Dermatitis.	Almost unlimited industrial causes: bacterial and fungal infections; drugs used for therapeutic purposes; mechanical and physical factors involving any portion of the body.	Types, sites, severity, diagnostic features too numerous to receive mention. Significance depends on exact cause and severity. R. M. I.	Apart from mild acne, mild seborrhea, mild erythema, mild sunburn, all skin rashes should be investigated. See subsequent references to distribution patterns of dermatoses.

Scars.	Obviously many; mechanical, chemical, infection.	Often serves as proof of previous disease states, such as chicken pox, smallpox, syphilis, "commemorative scars," i.e., smallpox vaccination; or identifies trades such as moulders from multiple burn scars on lower legs.	Scars suggest, when on thumb, shoemakers and skivers; on tongue, epileptics; when jagged on nose and face, windshield accidents; when short and straight above collar-bone, tuberculosis; when long and curved across neck, thyroid operation; long, linear scars, knife wounds; when jagged and furrowed, from gun shot accident; behind ears, mastoid disease; irregular, oblique on neck, scrofula; star-shaped at base of neck, previous tracheotomy; multiple burn scars on forearm, welders; pitted scars on back, shoulders and face, healed acne; pitted scars on forehead and face, chicken pox or smallpox.
Skin parasitism (scabies, pediculosis).	Animal parasites.	May be chiefly indicated by scratch marks. Lice or nits may be seen on hair. R. M. I.	Readily eliminated from intelligent persons; recurrences probable in unintelligent, unhygienic persons.
Skin atrophy.	May indicate normal senility or may constitute portion of damage from dermatoses; from many industrial causes.	Typical example—long standing x-ray dermatitis.	Some atrophy irreparable; further exposure elimination always desirable.
Capillary dilatations (chronic).	Many causes both industrial and nonindustrial, such as alcoholism and x-ray exposures.	Minor condition of obscure cause and significance; cosmetically unattractive.	If limited, sometimes may be removed by electrolysis.
Keloids.	Peculiar skin hypertrophy following superficial injury.	More common among Negroes; usually follows mechanical injury, such as incised wound; characterized by overgrowth of scar tissue at site of previous injury; tumorlike; multiple or single.	Occasional troublesome sequela of industrial injury.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Skin, *continued*	
Itching (pruritus).	Numerous; both industrial and nonindustrial.	Obviously not a visible mark. Scratch lines constitute the mark. May be associated with neurosis, dermatitis, parasitism, diabetes, leukemias. R. M. I.	Undue scratching of head suggests seborrhea or lice; scratching on back of shoulders, usually acne; scratching of feet, frequently fungal dermatitis; scratching in older persons, frequent in diabetics; scratching of anal region, parasites, fungal dermatitis, or neurosis.
Erysipeloid lesions.	Bacterial origin—staphylococci, streptocci.	Chiefly on hand and forearm. Highly common among fish handlers, particularly fish butchers. Commonest occupational disease on ocean liners.	May arise among butchers other than of fish. Often called "salt water sores." Mechanical injury from fish scales and bones may be a factor.
Swimmer's itch.	Caused by snail parasite *Schistosoma cercariae.*	As an occupational disease arises among fishermen, clam diggers, and other workers in outside waters.	The parasite lives in both fresh and salt water although exact form may be different.
Creeping eruption.	Animal parasite, larva migrans.	Burrowing parasite moves 1 to 2 cm. per day. Intense itching. Several parasites may be creating burrows at the same time. Not always occupational.	Common occupational disease in Florida among construction workers. Chiefly acquired from cat and dog feces. Condition known as Brazilian Hookworm. Several other parasites produce similar creeping eruptions.
Thresher's itch, Grain itch, Bunkhouse itch.	Animal parasite *pediculoides ventricosus.*	Chiefly limited to the threshing season. Acute dermatitis with pruritus.	May arise in manufacturing plants using straw for packing.
Rat mite dermatitis.	Liponyssus bacoti.	Common form of acute dermatitis with intense itching, urticaria. Commonly appears in areas under belts, girdles, bras, or socks.	Many other mites may produce human dermatitis.
Anesthesia, hyperesthesia, paresthesia.	Usually neuroses and unassociated with work; also chemicals, such as formaldehyde, phenol.	Not visible markings; encountered from complaints of increased localized skin sensitivity; numbness, burning, pricking; may be symptom in some occupational disease, such as arsenic poisoning. R. M. I.	More common among pharmaceutical workers, lepers, pneumatic tool operators.

Hair abnormalities (patchy baldness—alopecia areata).	Common causes—syphilis, arsenic, fungal infections; thallium, barium sulfides; synthetic rubber intermediates.	Industrially more important than widespread loss of hair because of possible industrial causation R. M. I.	Some forms of patchy baldness may involve eyebrows, beard, eyelashes, and the cause may be unknown.
Hair abnormalities (alopecia totalis).	Baldness in industry; may be caused by x-ray, industrial or medical.	Extensive baldness commonly unrelated to work causes, and perhaps more related to testicular function, heredity.	Any sudden extensive baldness or any baldness occurring in groups of workers quickly should be investigated.
Hair abnormalities (blue or violet colored hair).	Suspect improper or excessive hair dyeing; sometimes deliberate.	Usually unrelated to work, but various work materials settling on hair or scalp may impart divers colors.	Not disabling and usually temporary.
Hair abnormalities (localized canities).	Chiefly hereditary.	A fair number of persons present localized greying in midst of normally colored hair.	Ordinarily harmless condition existing from early life. Rarely associated with scalp, skin tumors.
Hair abnormalities (excess hairiness on faces of women).	Hormonal dysfunction.	In women cosmetic unsightliness from hair often associated with multiple indications of masculinity.	May appear first at puberty or only in later life.
Loss of nails.	Both industrial and nonindustrial causes, such as arsenic, fungal infection, alkalies.	Depends upon specific cause. R. M. I.	Frequently nails are slowly separated from bed among dishwashers, bottle washers, laundry workers, etc.
Watchmaker's nail.	Characteristic occupational stigma involving hypertrophy of left thumbnail.	Due to continual opening of watches.	Occurrence of condition on wane.
Beau's lines (transverse coloration of nails, brown or black).	Occur among mercury workers.	Arise in many forms of debilitating disease.	R. M. I.
Discoloration of nails.	Many industrial chemicals.	Many different colors produced, such as purple from acetanilid, brown from chromates, yellow from TNT, yellow from nitric acid, black from mercury, brown from photographers' chemicals, light yellow from picric acid, brown from hair dyes; many others.	Apart from contact, some nail discoloration may be produced as part of general involvement as in argyria.
Nail inflammation (and tissues immediately around nails).	Large number of industrial and nonindustrial chemicals; also nonindustrial infection.	Among many others, it occurs among confectionery workers, arsenic workers, bakers, bricklayers, chemists, dye workers; seek out particular exposure.	Nails themselves little subject to inflammation. See Chapter XIV.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Skin, *continued*		
Nail dissolution.	Many industrial keratin solvents; notably alkalies.	Complete destruction of nails rare; typical examples of causes—formalin, cement.	Outstanding feature inflammation of tissues adjacent to nails.
Nail deformities (thickening, curvature, pitting, linear markings, spotting).	Large numbers of industrial contact chemicals.	Common among furriers, dyers, lace makers, packers, cordage makers, thallium workers, auto washers, engravers, etchers, glass makers, miners, sulfide workers, x-ray technicians, string instrument players, tanners, many others.	Apart from infection, condition rarely disabling. White spots and transverse markings may indicate antecedent disease.
Vagabond's skin.	Lice.	Deep, patchy bronzing of skin from irritation of lice bite and possibly lice excreta.	Usually associated with low order of personal hygiene.
Morphea.	Unknown.	Diffused white spots, usually over torso and upper extremities representing a patchy scleroderma.	Startling when present on Negroes or other dark races.
Ichthyosis (fish skin).	Unknown but usually congenital.	Entire skin rough, scaly, thickened. Usually permanent.	Grossly troublesome to owner. Harmless to fellow-workmen.
Milker's nodules.	A virus disease (false cowpox). (Always associated with milking or udder cleaning.) Incubative period 5 to 7 days.	Usually involves exposed parts, chiefly fingers, hands, forearms. The reddish or reddish-blue nodules may be as large as 2 cm. in diameter. Sometimes as many as 40 present at one time. Mild systemic disease with lymphangitis, lymphadenitis may appear.	Self-limiting disease. Requires no treatment, but complications such as secondary infection may require treatment.
Barber's dermatitis (not Barber's Itch).	Mechanical punctures from customers' hair.	Chiefly limited to webs of fingers, or at least to fingers.	Burrowing sinuses made troublesome by secondary infection.
Hives ("Bold Hives" Urticaria).	Usually allergic causes. Many occupational excitants. Some forms related to photosensitivity.	Layman's "Bold Hives" means "giant urticaria." Gross lesions may appear in a few minutes usually accompanied by itching.	Urticaria may involve such tissues as around larynx and pharynx. Extreme edema may lead to prompt fatality.
Prickly Heat (Miliaria).	Related to profuse sweating. Common summer dermatitis. May occur in winter among cooks, bakers, bathhouse attendants, furnace workers, etc.	Commonly not an occupational disease but may be.	Common sites chest, back, axillary folds.

Fungicide Furunculosis.	While causes are multiple, such as "oil furunculosis," a specific type is caused by pentachlorophenol, an insecticide and fungicide causing gross furuncules and other skin eruptions.	New furuncules and acne may arise months after elimination of exposure.	Lesions not limited to exposed areas. Secondary infection may be prominent.
Chloracne.	Exposure to certain chlorinated compounds, chiefly waxes.	Characterized by extraordinary numbers of comedones, sometimes with typical acne pustules.	Systemic involvement may be associated.
Pathological sweating.	Many nonindustrial causes, but sometimes seen in lead poisoning.	Unusual sweating may be localized, odoriferous, colored, excessive. Sometimes found in heart disease, rickets, syphilis, palsy, tuberculosis, goiter, etc.	In arsenic or lead poisoning, abnormal sweating usually local to parts involved in neuritis.
Brick red (warm weather). Plum colored (cold weather).	Polycythemia(pathologic increase in numbers of red blood cells).	May be a manifestation of repeated exposure to carbon monoxide in relatively low concentrations. R. M. I.	Engorgement and congestion of superficial blood vessels. Most prominent on face. May involve conjunctivae.
Paroxysmal face and head flushing.	Chiefly associated with the menopause, this type chiefly limited to women 40 to 50.	May be associated with mental depression, excessive perspiration, weakness, insomnia, emotional instability.	Not occupational.
Lymphangitis.	Infection.	Red streak up arm or leg. Alarming indication of extension of localized pyogenic infection. R. M. I.	Frequently associated with "kernels" such as in axilla or groin.
Keratoses (farmer's warts).	Excessive sunlight, ultraviolet light etc.	Represent warty, flat, or horny, persistent overgrowth of outer layers of skin. Characteristic of past middle age life; usually limited to exposed parts of skin; characteristic of many trades including farmers, sailors, fishermen, gardeners, trappers.	Rarely become cancerous; readily removed by electrocauterization, by x-ray and by electric needle; less well by keratin solvents. Quite common both in and out of industry.
Asbestos warts.	Mechanical penetration by asbestos fibers; possibly chemical action akin to production of silicotic nodules.	Condition usually limited to fingers and hands.	Similar condition with glass fiber workers, but in that case always mechanical.
Tumors (on skin).	Several types, both benign and malignant. Commonest variety, epithelioma.	Apart from nongrowing warts and obvious abscesses of skin, any enlarging mass on or in skin should be investigated. R.M.I.	Pigmented moles are prone to become malignant.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Skin, *continued*	
Tumors (beneath skin).	Frequently harmless, fatty tumors (lipomas). Attain to large size.	Because of uncertainty, every mass beneath the skin should be investigated by a physician.	Skin over lipomas, if squeezed, becomes dimpled, "orange peel" sign. See next item.
Subcutaneous lymph nodes (enlarged).	Lymph nodes of neck, axilla, groin, etc., may become enlarged and observable; many causes, but chiefly infection. "Kernels."	Depends upon precise cause of gland enlargement. R. M. I.	Lice in head hair frequently is cause of enlarged lymph glands on sides of neck.
Skin cysts.	Plugged-up oil glands.	Large or small sacs in skin with fluid or pasty content; few or numerous cysts may appear almost anywhere on skin surface, particularly about head; on scalp called "wens"; relatively harmless; disfiguring.	Milium "white heads" ordinarily represent multiple minute cysts.
Work callosities.	Pressure and friction.	Characteristic of many trades, the exact location usually identifying the trade or profession, e.g., fingertips in harp players, base of little finger in bundle tiers, hod carriers on shoulders, sailors on abdomen, hand type setters on fingertips, violinists on left jaw, basket makers on outer edge of palm, engravers on little finger, wood cutters on face, porters on palms and shoulders.	Callosities are often more revealing of a trade than important as disease state. Merely skin hypertrophy of fingers, hands, feet, or other local portions of body.
Skin corrugation (rugosity).	Several nonindustrial causes; outstanding cause in industry, tannins; less definitely alkalies.	In tan yards, some workers' skin of hands literally may be tanned, grossly rugose and brown discolored. From alkalies, hypertrophy with fissuring is common; somewhat dissimilar to rugosity; many other examples.	Tendency to recover on elimination of exposure; some permanent damage.
Skin hemorrhage (purpura).	Many nonindustrial causes including infection, tuberculosis, cachexia, endocarditis. In industry suspect benzol.	Always significant. R. M. I.	In benzol poisoning may be associated with bleeding from gums, nose, genitalia.

"Birthmarks."	Never industrial, and not properly "birthmarks."	Area of birthmarks sometimes more susceptible to action of industrial irritants, pressure, etc.; may become cancerous.	To eliminate disfigurement, many so-called "birthmarks" may be removed by electric needle, x-ray.
Hypodermic skin markings.	Improper or extensive use of hypodermic needle.	Marks the hypodermic introduction of drugs, such as morphine or insulin.	Usually important to rule on the desirability of work applicants—drug addicts, diabetics. On side of chest, may be associated with collapsed lung in tuberculosis.
		Skin Patterns	
Pattern contact dermatitis.	Variety of chemicals.	Distribution and shape of lesions commonly reveal the cause. Almost unlimited varieties such as peculiar distribution of lesions from handling bowling balls, hairpins, combs, wristwatch bands, shoelaces, door knobs, steering wheels, brief case handles, cigarette lighters, hat bands, spectacles, etc.	Extensive information chiefly developed by Waldbott in his *Contact Dermatitis.*
Lesion distribution.	Contact dermatitis.	Common distribution—back of hands and fingers, wrists, forearms (any surface), elbow folds, upper arms, neck and face, but not scalp; waistline, thighs, lower legs, with no or little involvement of chest or back, knees or feet. R. M. I.	Apart from traumatic injury, palms are seldom primarily involved in industrial dermatitis.
Lesion distribution.	Psoriasis.	Elbow points, knee caps, palms, back of head, shins, abdominal wall. R. M. I.	This distribution almost rules out all industrial dermatitis.
Lesion distribution.	Cutaneous syphilis.	Characteristic distribution — palms, cheeks, forehead, chest, abdomen, genitalia, anal region, soles of feet. R. M. I.	Almost opposite that of industrial dermatitis.
Lesion distribution.	Erythema multiforme (papular erythema).	Characteristic distribution—back and front of hands but not fingers; front of wrists, around elbows, around mouth, forehead, rarely on torso, rarely on thighs, front of knees, front of feet. R. M. I.	This distribution varies greatly.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Skin Patterns, *continued*	
Lesion distribution.	Acne.	Shoulders, chest, neck, face but not scalp, back.	Lesions and distribution quite dissimilar to industrial dermatitis.
Lesion distribution.	Shingles (herpes zoster).	Characteristic distribution follows nerve courses; front of arms, forehead and upper face, obliquely on chest and abdomen, outer surface of thighs, rarely around shoulders, rarely below knees. R. M. I.	Associated with much more pain than many forms of dermatitis.
Lesion distribution.	Seborrhea (on oily skin).	Scalp, forehead, sternal region, armpits, midway between shoulders, genital region; practically never on back or abdomen.	Seborrhea on dry skin may have different distribution and chiefly involves extremities.
Lesion distribution.	Scabies (itch).	Webbing between fingers, palms of hands, armpits, breasts in women, around and on genitalia, between buttocks. R. M. I.	Less frequent in lower extremities.
Lesion distribution.	Mycotic dermatitis (ringworm).	Palmar surfaces of fingers and hands including webbing of fingers, but seldom backs of fingers and hands, forearm, scalp, bearded region, midsection of chest (certain varieties), around genitalia, anal region, between toes, soles of feet, around ankles. R. M. I.	Fungal lesions as seen in industry seldom are characterized by the circular involvement with clearing center.
		Eyes	
Blindness (in industry usually partial).	Arsenic, benzol, carbon monoxide, hydrocyanic acid, hydrogen sulfide, lead, methanol, nitroglycerin, tobacco, trauma; many nonindustrial causes.	The pathology of industrial blindness as occupational diseases varies highly; e.g., from methanol, optic neuritis; from benzol, intraocular hemorrhage. R. M. I.	Many other substances than those listed may impair vision.

Cataracts.	Usually not an occupational disease, but traditionally associated with glass making, furnace work, and other incandescent operations. Common from penetrating foreign bodies around lens. Frequently congenital, and frequent among diabetics.	Disappearing as an occupational disease. R. M. I.	Use of suitable eye protection in hot and excessively luminous industries is preventing the occurrence of cataracts.
Conjunctiva (yellow-brown pigmentation of conjunctiva and cornea).	Many chemical causes, chiefly aniline and its derivatives, particularly hydroquinone.	May be accompanied by reddish discoloration of hair and skin of hands and feet.	Rare condition.
Conjunctivitis.	Almost unlimited; nonindustrial and industrial agents, such as vapors, acids, dust, ultraviolet rays (Klieg eye).	Seek out particular cause. Frequently associated with respiratory tract inflammation. R. M. I.	One of commonest manifestations of industrial irritants. One red eye more likely to be industrial than two red eyes.
Conjunctival xerosis (dry eye).	Vitamin A deficiency.	Thickening of conjunctivae over eyeball; vascular injection with growth over corneal margin in severe cases.	More general distribution than pterygium.
Exophthalmos (protruding eyes).	Usually bilateral from hyperthyroidism; monolateral from brain or eye tumors.	Commonly unrelated to work exposure; causes staring expression. R. M. I.	Associated with tremors, sweating, flushed skin, agitation, other aspects of thyroid syndrome.
Xanthelasma (buttery eyelids).	Caused by fatty degeneration. Occurs chiefly in elderly patients, women more often than men.	When prominent, gives startling appearance to eyes.	Harmless except for cosmetic unsightliness. Frequently removed surgically by those who can afford it.
Abnormal pupil size.	Caused by many drugs such as pin-point pupils by morphine.	Pupil size abnormalities frequent from occupational diseases, as among pharmaceutical workers handling such chemicals as atropine.	R. M. I.
Strabismus (cross eyes).	Commonly congenital. May arise after one-eye blindness.	May be divergent or convergent. Congenital strabismus not always manifest in infancy.	May arise as acute state after brain hemorrhage.
Discoloration of eyes (blue sclera).	Familial disease unrelated to work.	Part of well-established syndrome of brittle bones and blue sclera.	For confirmation, observe other members of the family.
Discoloration of eyes (yellow sclera).	Usually jaundice.	Reflects liver damage possibly from industrial causes, such as carbon tetrachloride, or instead, infection or cancer. R. M. I.	Look for jaundice of skin or bile in urine.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Eyes, *continued*	
Discoloration of eyes (slaty grey sclera).	Part of picture of argyria.	Produced by silver.	Does not always occur in argyria.
Discoloration of eyes (purple sclera).	Methyl violet.	External entry of traces of indelible pencil or some ball pen inks. R. M. I.	Methyl violet, in addition to abnormal coloration, may induce definite irritations and rarely ulcers. Temporary.
Discoloration of eyes (mineral specking).	Several mineral dusts.	Various mineral dusts, such as iron, mercury, calcium, may induce spotty, colored deposits; color depends upon metal.	Does not always arise in presence of mineral or metal dusts; black specks also produced among workers melting sealing wax; also phenol.
Discoloration of eyes (misc.).	Various dyes and other industrial and therapeutic agents; lack of vitamins.	Relatively unimportant; staining of eyes from accidental or deliberate introduction of divers agents.	Usually unimportant and temporary except in avitaminosis.
Arcus senilis.	Usually old age.	White circle or arc at periphery of cornea.	May occur in premature old age.
Impairment of color vision (temporary—not color blindness).	Few drugs, such as santonin, tobacco.	Temporary loss of color judgment.	Santonin possibly may discolor eye humors.
Restriction of color field.	Chlorinated hydrocarbons; possibly other substances.	Does not appear as a visible sign; attracts attention on complaint of worker. R. M. I.	More frequently from nonindustrial causes.
Diplopia (double vision).	Usually nonindustrial, but may be caused by emetine and possibly other substances.	R. M. I.	Common feature of alcoholism.
"Doll's eye."	Postdiphtheritic paralysis.	Dissociated movements of head and eyes; when head is raised, the eyes are lowered, etc.	Sometimes associated with protruding eyeballs.
Impaired movement of eyes or lids.	Many nonindustrial causes; may be a feature of some industrial diseases as lead poisoning.	Many types of paralysis. R.M.I.	Droopy eyelids, hollow cheeks, fatigued expression, suggests myasthenia gravis.
Nystagmus (fine repetitive motions of eyeballs).	Neuroses; fatigue, ear disease.	Fairly frequent among miners, train dispatchers, jewelers, draftsmen. R. M. I.	Eye motion may be lateral, vertical, circular or combined.
Deposits in or around eyelids (misc.).	Deposits of fat, pus, fibrous tissue or pigment.	May represent abscesses, cysts, or calcareous formations; many varieties.	Certain deposits suggest diabetes or gout.

Trachoma (granulated eyelids).	A virus disease.	This condition is readily communicated to others.	Commonly described as a filth disease occurring and spreading chiefly under conditions of uncleanliness.
Pterygium.	External chemical or mechanical repeated minor injuries.	Wedge-shaped film growing from angle of eye toward and sometimes covering cornea; resembles eye condition in certain avitaminoses. R. M. I.	Occurs among lime burners, stonecutters, masons, sand blasters, and varnish cookers.
Intrascleral hemorrhage.	Rupture of minute blood vessel with filming of blood between scleral layers.	Alarming bright red in appearance, but usually without medical importance. May be related to high blood pressure.	Goes through usual stages of ecchymotic clearing, that is, purple, yellow, etc.
Sty (hordeolum).	Staphylococcus infection of eye glands.	May be single or multiple.	Ordinarily unrelated to work causes. Common among diabetics.
Chalazion (bump in upper eyelid).	Mechanical stoppage of gland ducts.	May be noninflammatory.	Frequently occur in crops, tendency to recurrence.
Ectropion (pulling down of lower eyelid exposing eyeball).	May follow contraction of scars, wounds, burns, or chronic conjunctivitis.	Commoner in old workers.	Unrelated to work except as a result of scarring from work injuries.
Puffiness of eyelids.	May be early sign of arsenic poisoning.	Frequently associated with other characteristics of eye or respiratory infection. R. M. I.	Observe for additional swelling above eyebrows. If not infection, establish possibilities of arsenic exposure.
Iritis (injection of white of eye around colored portion of eye).	Chiefly infection.	Common consequence of small neglected eye injuries such as from foreign bodies.	Warning of beginning of serious situation. R. M. I.
Cloudy cornea.	Usually unrelated to work.	May represent beginning glaucoma. R. M. I.	Usually associated with foggy vision, severe pain in eye, dilated pupil, swelling of conjunctivae and lids.
Pearly sclera.	Pearly white or pearly blue sclera, usually associated with anemia.	May be associated with occupational anemias. Highly brilliant eyes produced by drugs, and especially in women. R. M. I.	Frequently suggests anemia, particularly when conjunctivae are pale pink.
Photophobia (intolerance of light).	Eye strain.	May indicate uncorrected defects in vision. R. M. I.	In industry may be related to excess light, either natural or artificial. Glare.
		Nose	
Rhinitis—"running nose."	Infection or chemical irritation of nasal passages.	Obviously one of commonest nonoccupational affections and one feature of irritation from numerous industrial gases, vapors, dusts, etc.	Rhinitis may appear on an allergic basis from both industrial and nonindustrial causes.

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Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
Nose, *continued*			
Rhinophyma (bulbous nose).	Related to acne rosacea.	Hypertrophy of nose and nearby tissues; not associated with industry.	Sometimes associated with alcoholism; largely unproved.
"Saddle-nose."	Congenital syphilis.	May be due to trauma.	May occur in acquired syphilis.
Infected nodules with severe systemic disease.	Glanders.	Rare disease commonly limited to horse tenders. R. M. I.	Nodules discharge yellow, glary pus with offensive odor.
Nose bleed (epistaxis).	Many nonindustrial causes. If industrial, caused by irritant gases, dusts, or mists such as chromic acid, benzol, or fluorides.	If profuse and repeated, R. M. I.	May be associated with foreign bodies in nose, deviated septum, many infectious diseases, such as measles, various forms of anemia, cancer, etc.
Ears			
"Cauliflower" ears.	Trade-mark of the pugilist.	Fibrous deposits in external ear.	In the absence of protection, may arise among military tank operators.
Noise deafness (cocked good ear is the visible sign, or attitude may indicate deafness).	Noise.	Temporary or permanent deafness or impaired hearing to some or many frequencies; probably originates on a fatigue basis followed by organic impairment. R. M. I.	Usually bilateral, even when one ear is protected against noise. Deafness in one ear, if occupational, may arise in train dispatchers, telephone operators, etc.
Deafness (impaired hearing other than from noise).	Various substances, such as lead, hydrogen sulfide, carbon disulfide, are credited with capacity to produce deafness.	Often difficult to differentiate between industrial and nonindustrial deafness; normally occurs in old age. R. M. I.	Deafness may constitute a neurosis.
Impacted cerumen (wax-plugged ears).	Ear wax as such, or mixed with dusty materials.	Common minor affliction in and out of industry, particularly dusty trades; signs of hearing impairment constitute mark. R. M. I.	Readily may be remedied by softening and washing.
Aural dermatitis (ear itch).	Varied; external irritants, infection, systemic impairment, lack of vitamins.	The ears are common sites for many forms of dermatitis and other dermatoses. R. M. I.	Noise-preventing and hearing appliances may favor aural dermatitis. Ear scratching prominent sign.
Otitis media (running ears).	Infection.	Common ear disease of all ages; frequent in industry, but not often caused by it. R. M. I.	A frequent source of subsequent deafness.

Equilibration disturbances (Ménière's disease).	Dysfunction of semicircular canals. Falling without obvious cause is the objective sign.	Any defect of equilibration of grave importance in airplane operators. R. M. I.	Probably related to sea sickness, train sickness, etc.
Gangrene.	In industry, frostbite.	In absence of history of frostbite, suspect diabetes. R. M. I.	May be caused by infection.
Trophi.	Gout.	Characterized by numerous hard, yellowish, round, pointed nodules at ear margin.	Similar nodules may appear on various portions of body, such as feet.
Increased hearing (overirritation by noise).	Alcohol and/or tobacco poisoning.	Pathologic irritation by moderate noise.	Also caused by certain neuroses, quinine and salicylic acid poisoning, and migraine.
	Lips, Mouth, Teeth, Tongue, Neck		
Cornification of lips (thickening of lips).	Mechanical pressure and friction on lips.	Characteristic of many trades or professions, such as wind instrument players, glass blowers, etc.	Nondisabling.
Lips (cancer, epithelioma).	Exact cause unknown.	The lips are perhaps the most common site of epithelioma. R. M. I.	Rarely related to industry as the cause; said to be common in fishermen from tar on fish nets and the holding of net thread between lips.
Lips (encrustation and ulceration).	Attributed to arc welding and presumably ultraviolet rays in absence of protection.	In some welding, eyes only are protected. Undesirable.	May represent precancer lesion.
Cheilosis (one form of inflammation of lips).	Riboflavin deficiency.	Pallor of lips with maceration of mucosa; may be one indication of vitamin lack.	Common among industrial workers; not directly related to work as a cause.
Rhagades.	Congenital syphilis.	Fissured inflammation, or scars therefrom at angles of mouth.	Not to be confused with cheilosis from vitamin deficiency.
Tongue (greenish-black).	Vanadium pentoxide dust.	One item in syndrome. Among others dyspnea, emphysema, bronchitis, hypertension.	Rare affection.
Swollen tongue.	If industrial, suspect ingestion of corrosive poison, phenol, cresol, mineral acids, mercury, etc.	Many causes unrelated to work, such as cretinism, infection, cancer, actinomycosis. R. M. I.	When due to industrial material, usually accidental or suicidal.
Tongue (scars from epileptic tongue biting).	Epilepsy.	Some epileptics will present evidence of fresh or healed damage of the tongue from biting during seizures. R. M. I.	Evidence of tongue chewing does not constitute proof of epilepsy.
Coated tongue.	Constipation, gastritis, dehydration, vitamin deficiency.	Relatively unimportant.	Rarely coated tongue in colors such as black may be due to fungal infection.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		Lips, Mouth, Teeth, Tongue, Neck, *continued*	
"Beefy" tongue.	Vitamin B deficiency.	One manifestation of vitamin B lack. R. M. I.	Enlarged tongue, roughened, rugose and red; somewhat resembles raw beef.
Herpes (labial)—"cold sores."	Action of a virus, allergy.	Virus probably always present but only becomes active under unfavorable conditions such as infection.	Not to be confused with labial chancre.
Occupational fungal disease around mouth.	Condition limited to Mediterranean countries. Involves chiefly quail force-feeders.	Organism transferred by quail pecking feeders' faces.	Condition not known in United States.
Discolored gums.	Various metal or mineral deposits, tobacco stain, etc.	The purple gum line of lead absorption, the similar line from bismuth, the blue line following trinitrotoluene exposure or poisoning, purple line from copper, bluish line from mercury or zinc, purple gums from scurvy. R. M. I.	Lines or discoloration of gums are not conclusive proof of any occupational disease.
Burton line (lead line).	Bright purple line at gum margin. Common after exposure to lead.	Not diagnostic of lead poisoning.	Not readily visible as a sign of abnormality. R. M. I.
Acute multiple dental caries.	Specific form attributed to work with citric acid, chiefly bakers and confectioners.	Well recognized in European countries. Uncommon in exaggerated form in United States.	All sugars as used in bakeries and confectionaries may produce some excess of dental caries.
Dental erosions.	Erosion from chemicals, such as from acids or mechanical erosion such as from glass blowers' pipes; numerous variations; specific variations for many trades, such as battery makers from acid, sewers from thread biting, wind instrument players, "tack spitters," brush makers who trim bristles by biting, pencil chewers in offices.	Profoundly eroded teeth of acid workers seldom decayed and are not painful.	Apart from dental erosion constituting a sign of occupational damage in many trades, the premature loss of teeth may possibly be related to work as a contributory cause.
"Mulberry molars."	Congenital syphilis.	Dome-shaped, stunted first molars due to overgrowth of enamel.	Various other dental defects suggest congenital syphilis.
Hutchinson's teeth.	Congenital syphilis.	Notched incisors with narrow edges and peg topped.	May be associated with impaired hearing and baked cornea.

Discolored and mottled teeth.	Fluorine is the cause of characteristic mottling, but many metals such as copper and iron bring about diffused coloration.	Apparently no great harm produced by many forms of teeth coloration.	Smoking, and particularly pipe smoking, may lead to black deposits on teeth.
Speech defects (not visible defects).	Highly varied causes—brain tumors, syphilis, neuroses, fatigue, etc.	Stammering, slurred speech, monotonous speech, explosive speech, aphonia, etc. R. M. I.	Stammering may be related to improper management in childhood of left-handedness.
Goiter (hyperthyroidism).	Enlarged thyroid gland.	Common as simple goiter due to iodine deficiency. Also toxic goiter from hyperthyroidism. R. M. I.	More common in women.
Salivation.	Industrial causes—mercury, potassium chlorate, phosphorus, copper, bromides.	Excessive formation of saliva. R. M. I.	Scores of nonindustrial causes, such as Vincent's angina, mumps, cancer, syphilis, scurvy, etc.
Mouth breathing (open mouth).	Numerous causes unrelated to work, such as adenoids. If associated with dyspnea, may be caused by silicosis, which is rare.	Mouth breathing may be caused by nasal obstruction. R. M. I.	If related to recent injury to face, suspect dislocation of jaw.
Breath (garlic odor).	If not garlic, then possibly tellurium, selenium, or arsenic.	Persists months after termination of exposure.	Disappears after increased intake of ascorbic acid. Odor will return unless use of ascorbic acid is long continued.
"Phossy Jaw."	Yellow phosphorus.	Deformity from necrosis of facial bones, chiefly lower maxillary.	Condition now rare. Formerly common among match makers, fireworks manufacturers, rarely fertilizer operatives.
		Chest	
Bulging of breast bone (sternum).	If associated with pulsation, suspect aneurysm; if chicken-breast-like, suspect rickets; if series of knobs on either side at rib section, suspect rickets.	Any marked external protrusion should lead to medical observation.	Converse picture that of depressed sternum frequently called "cobbler's chest" associated with shoemakers' trade as cause. Now rare.
		Extremities Apart from Skin	
Ganglion (ganglia).	Cysts in the region of joint capsules and tendon sheaths.	May occur along any tendon sheath or about many joints but more common on hands and feet; may be either industrial or nonindustrial.	Frequently attributed to coarse vibration as from pneumatic tools.

(continued)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Extremities Apart from Skin, *continued*		
Bursitis (excess fluid around joints).	Friction, pressure, or infection.	Bursae are potential spaces in connective tissue around joints that grow in response to functional demand. R. M. I.	Many varieties constitute occupational diseases, as in "beat elbow" in miners.
Clubbed fingers.	Congenital, or may be related to heart disease.	Various occupations lead to some bulbing of finger ends from hypertrophy; cause of the relationship to silicosis and heart disease obscure.	Many other variations in shape of fingers. Toes may be clubbed.
Joint enlargement (arthritis).	Usually infection and gout.	Bony enlargement frequently called rheumatism, usually in error; ordinarily represents reaction of infection or infection products.	Some occupational diseases, such as lead poisoning, infrequently lead to bone and joint enlargement.
Varicose veins.	Hydrostatic pressure, infection among others.	May appear anywhere, but most common in lower extremities; little related to work as a cause.	Frequently associated with indolent ulcers.
Flat feet (pes plenus).	May be congenital; may result from weight bearing; may be related to degeneration of senility.	A well-known common affection important to industry but little caused by it.	May be influenced for good or bad respectively by good or poor footwear.
Saber shins.	Congenital syphilis.	Forward bending and thickening of middle third of tibia.	Knobby shin bones in absence of saber deformity also suggests syphilis.
Wrist drop (wrist weakness).	Metal poisoning, usually lead or arsenic. Alcohol.	A frequent feature of lead poisoning; its counterpart is ankle drop; seen in lead poisoning when leg muscles are much used. R. M. I.	Many other muscle groups similarly may be weak in metal poisoning, and chiefly in lead poisoning.
Tremors	Different causes for different types.	Many types involving many portions of the body from fingers to tongue. May be related to various diseases and states, including fear, goiter, Parkinson's disease, lead poisoning, etc. R. M. I.	Some tremors cease on the accomplishment of an intention; thus a marked tremor may exist in reaching for a book and cease when the book is picked up.

Dead fingers (white fingers).	Cold associated with vibration.	This condition is akin to several others involving capillary blood supply to fingers; some conditions unrelated to cold or vibration, such as Buerger's disease. R. M. I.	Has occurred among marble cutters working with vibrating tools in cold weather in outside sheds; persists for months.
Writer's cramp.	At times, a neurosis; at times caused by local fatigue.	When apart from neurotic influence, writer's cramp constitutes a good example of localized fatigue; ordinarily involves those fingers and those muscles employed in any particular form of writing. R. M. I.	Cramplike pains may occur. Actual site of damage not in fingers but in arm.
Stereo movements.	Habit; continuation of work movements after work.	In some occupations requiring highly repetitive small motions, these motions are continued long after work hours. No disability, but some significance related to monotony effects, etc.	Well presented years ago in famous comic motion picture.
Baseball finger.	Blow by baseball on end or palmar surface of finger.	Somewhat characteristic swelling and deformity, usually limited to one joint of one or more fingers.	Common among industrial workers and fairly common basis of claims for compensation.
Dupuytren's contraction.	Shortening of the palmar fascia.	Permanent flexion of little and ring fingers (at times all fingers) with rigidity of palmar tissue. May be caused by infection, may result from oft-repeated severe pressure on palm. Said to be common among upholsterers.	Rare before middle age. Associated with arthritis.
Trigger finger (snap finger).	Injury to fingers in or out of industry.	Difficulty in extending fingers, but after great effort fingers fly out like jackknife blade.	A corresponding condition may exist in toes.
Sclerodactylia (deformed, pigmented fingers).	Unknown, but probably unrelated to work.	One, and usually more, fingers of both hands become withered, shortened, deformed, nodular, waxy-white, and at times brown or black pigmented. R. M. I.	Much worse in cold weather.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
	Extremities Apart from Skin, *continued*		
"Red Hands."	Often purely psychogenic. At times specific chemical cause, such as oxalic acid.	Patch tests usually negative.	Barrier creams sometimes effective, possibly constituting only psychotherapy.
Seal finger, Spekk-finger, Blubber finger.	Infection.	Chiefly limited to Arctic sealers.	May arise among seal furriers anywhere.
	General and Miscellaneous		
Edema.	Immediate cause—increased fluid in tissue.	Edema may occur in any tissue, organ, or system from ankles to eyelids. Ordinarily not a disease in itself. R. M. I.	Edema around ankles after long standing in the absence of known disease may not be important.
Pathologic sleepiness (somnolence).	If organic, may be related to pituitary disease or other glandular disorders. Commoner in obese or giant-sized persons. Sometimes appears in early pregnancy.	May only represent lack of proper sleep. May be associated with alcoholism. May be a symptom of various occupational diseases. R. M. I.	Many workers, particularly on late night shifts, now indulge in drug stimulation, chiefly caffein. Many proprietary preparations available. Caffein poisoning in industry is a ready possibility.
Sunstroke.	Chiefly direct exposure to sun's heat. Less frequently artificial heat.	Represents derangement of heat-regulating system of body. R. M. I.	Chief characteristics—high body temperature, hot dry skin, loud breathing, unconsciousness; in early stage eye pupils dilated, later contracted.
Myxedema (hypothyroidism).	Lowered functioning of thyroid gland.	More frequent among women. R. M. I.	Characterized by dull, heavy features, thickened, swollen skin, some loss of hair, subnormal temperature, sleepiness, joint pains, constipation.
Shaking palsy, Parkinson's disease.	Unknown.	Rare before middle age. R. M. I.	Chief features—shaking of head, tremors of hand and arms, muscular rigidity, masklike facies, propulsive gait; some similarity to manganese poisoning.
Barrel-shaped chest.	Common among asthmatics, fairly common among glass blowers, less frequent among musicians, i.e., singers, wind instrument players.	Associated with pulmonary emphysema (dilation of lung sacs). R. M. I.	During asthmatic attack, there may be either skin pallor or cyanosis, anxious facies, violent respiratory movement, short inspiration, long, wheezy expiration.

Tics.	Spasmodic contraction of any portion of body, such as cheek, tongue, eyelid, fingers. Not directly related to industry.	Common among neurotics.	Tics are frequently called "habit spasms."
X-ray gangrene.	Improper x-ray exposure.	Begins like common skin burn but advances to deep ulceration and sloughing. Usually involves fingers and hands. R. M. I.	Common among older x-ray workers and technicians. Frequently seen among factory workers and industrial workers as a result of poor x-ray treatment for dermatoses.
Phenol gangrene.	Extensive or prolonged contact with concentrated carbolic acid (phenol).	Following accidental and painless contact with carbolic acid, fingers, hands or other parts become brown, dry, shriveled, and finally black, with possible eventual spontaneous amputation. R. M. I.	May arise apart from industry from accident or poor medication.
Scurvy (sailors' scourge). Chiefly manifest by bruised appearance of legs, edema (chiefly of ankles) profound, weakness, loss of weight, loss of teeth, bluish, reddish, blackish spongy gums, heavily coated and brownish tongue.	Vitamin C deficiency.	As occupational disease now rare. Term "scurvy" chiefly has disappeared although vitamin C deficiency of mild degree is highly common.	Still might arise occupationally among explorers, seamen, remote mining and lumber camps, dietary cranks, etc.
Erethism (pathologic shyness).	In industry chiefly seen as manifestation of mercury poisoning.	In mercury poisoning many patients are extraordinarily bashful, awkward, assume rigid poses.	Seen in other conditions unrelated to industry.
Enlarged glands (lymphadenitis).	Chiefly in infections but may indicate malignancy.	Often occurs on sides of neck, under arms, and in inguinal regions. "Scrofula," now rare, represents TB of glands, chiefly of neck.	Head lice may be accompanied by enlarged glands. R. M. I.
Hernia (inguinal). Enlarged mass in inguinal region.	Condition usually represents congenital defection. Trauma as ultimate cause rare but possible.	Usually unilateral. May be bilateral.	Common cause of partial or temporary disability.
Hernia (umbilical).	Protruding mass from abdomen around navel.	More common among women than men.	Rarer than inguinal hernia.
Hydrocele (water in scrotum).	Relates to inflammation. Specific cause uncertain.	May be unilateral or bilateral.	May be associated with inguinal hernia.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*continued*)

Mark or sign	Probable cause	Significance	Comment
		General and Miscellaneous, *continued*	
Facial paralysis.	Nerve damage such as from toxic agents or trauma.	A common variety reveals mouth drawn to one side, drooping eyelids, impaired articulation.	Can arise as manifestation of occupational disease.
Paroxysmal asthma.	Commonly spasmodic asthma is an allergic disease unrelated to industry.	As one manifestation of occupational diseases, paroxysmal asthma occasionally may arise in such conditions as trichloroethylene poisoning, chlorine bronchitis, etc.	R. M. I.
Effeminization of males.	Stilbestrol and similar agents.	Limited chiefly to pharmaceutical workers processing hormone-like chemicals. May be characterized by enlarged breast in males, production of feminine type of body, sexual impotency.	Legally held to constitute an occupational disease. Manifestations may subside after elimination of exposure.

Mark or sign	Characteristics
Abnormalities of gait.	The manner of walking, together with the carriage of the entire body, may afford a true insight into precise disease states, or at least may indicate abnormality to the point that a medical investigation should be carried out. It is difficult to describe in a few words the peculiarities of gait, even though on observation abnormality be quite obvious. For this reason, resort to tabular presentation is for the moment abandoned. Many peculiarities of gait call for no description since the provoking cause is at once evident. Such, for example, are the waddling gait of the woman in advanced pregnancy, the worker with an artificial leg, the victim of a stiff knee, the many types of gait abnormality following infantile paralysis, the gait occasioned by shortening of one limb, the tottering, generally unstable gait characteristic of senility or convalescence from disease. In other states, some of which are clearly occupational, gaits, while characteristic, may be less obvious as to cause. In any peripheral neuritis of the lower limb, e.g., from *lead* or *arsenic*, the resulting ankle drop or weakness may lead to a revealing gait. In such instances the leg is lifted high with exaggerated knee action, the foot is thrown forward, and the ground or floor is slapped at each step. The shoe is worn at the toe. Although the condition is commonly bilateral, when unilateral an obvious variation is induced. The gait of the worker under the influence of *alcohol* exposes his condition. The gait is staggering, tottering, reeling. Alternately the body may be leaned forward, backward, or sideward with purposeless lurching. The drunk, apparently about to fall with each step, rarely does so. The gait in *manganese* poisoning is called the "rooster gait." There is propulsion with ever-increasing rapidity, until the victim may catch himself on some support; otherwise he may fall. If he starts backward, retropulsion becomes the obvious counterpart of propulsion.

In some forms of central nervous system *syphilis*, the gait is ataxic. The patient walks with his eyes on the ground, and in some severe circumstances may not walk without seeing every step. Manifestly, this gait is worse at night, and some patients with this disease fall to the ground whenever their eyes are closed. In this gait, the feet are turned out and the legs are far apart. The leg movements are excessive and the feet lifted too high. In this instance, the heels come down sharply, as may be proved by unusual wear on the heel.

When one leg is paralyzed, as in *hemiplegia*, the afflicted leg is rigid and moves as a part of the body as a whole. The leg is thrown outward, swinging in a semicircle and with a motion toward the trunk. Thus, shoes will be worn down on the outer side.

In *palsy* (paralysis agitans), the steps are short and shuffling, with a tendency to walk faster and faster, as in manganese poisoning. This gait may be accompanied by a variety of tremors of hand and head, and is associated with a characteristic speech.

In *sciatica*,the afflicted leg is kept in a position of slight bending with the heel raised and in walking, the chief pressure on that side is limited to the front part of the shoe, which part shows most wear.

Many *epileptics* exhibit no gait peculiarities, but some in well-established instances have a gait characterized by slouching and apparent weakness.

In *Huntington's chorea*, a rare disease, the gait is associated with motion in all parts of the body. The arms, head, and legs move from side to side, as well as forward. There is continuous rocking and lurching with flinging motions interspersed with momentary periods in which the whole body is at a standstill.

In *hysteria* and *malingering* involving the lower extremities, the assumed gait may be so bizarre as to arouse suspicion that no organic lesion exists. Variations are almost limitless. One neurotic may push an imaginary lame leg along as though on a skate; another may drag the foot with the top of the toes downward; another may walk on the outer edge of one or both feet. Occasionally the motion made may suggest the arc of a scythe. All of these gaits possess some feature apart from the characteristic gait of any organic lesion.

In *mercury* poisoning there may be no involvement of a lower extremity, but on occasion may be characterized as a running gait.

At least 50 other conditions unrelated to work as a cause, but occurring among workers, may be observed ranging from the ordinary limp due to corns, injury, gout, inguinal or pelvic abscess, to the complex gait of Thomsen's disease in which the legs are alternately stiff.

Abnormalities of facies.

The countenance may in itself disclose disease states, some few of which may be related to occupation. The most characteristic peculiarities of facies are related to disabling diseases, of a type not seen in workers on duty, for example, the facies of typhoid fever. Some facies that may give clue to diagnosis are now mentioned.

In the *dyspneic* facies, the mouth is open, the lips are dry, the nares dilate with each inhalation. The face may possess a bluish pallor, the expression is one of anxiety. This condition might be found in well-established silicosis, in heart disease, and in some types of asphyxiation.

Manganese facies may be characterized as masklike. The skin is without wrinkles, the countenance without expression and comparatively motionless—doll's face. Other diseases of the central nervous system may give rise to masklike facies.

In the presence of *adenoids*, and more particularly in persons younger than those in industry, the face is likely to be long and hatchetlike, the expression is dull, the nares pinched, the mouth open and prominent, the lips dry, the eyelids droop.

(*continued*)

Common External Marks of Occupation or Occupational Diseases or Other Diseases (*concluded*)

Mark or sign	Characteristics
Abnormalities of facies (*continued*)	In *neurotics* and *hysterical* persons, the facies may give a hint that such states exist. The expression is characterized by amiable but silly smiling on an otherwise empty face, or instead repeated but not continuous frowning may take place in the absence of any reason for such. Irregularly these faces exhibit facial tics. The facies of congenital *syphilis* are characteristic in adults. The forehead is overhanging and bumpy, the bridge of the nose is depressed (saddle nose), linear scars radiate from the angles of the mouth. Hutchinson's teeth, elsewhere described, may be present. Occasionally a patient with beginning but well-established *pneumonia* may be still at work. Although the characteristic facies may not have established themselves, they, if present, will show a flushed skin, the breathing may be rapid and hurried, and possibly associated with a grunt at the end of every exhalation. Herpes may be present; the eyes glisten; the expression is that of anxiety. In some cases of *hyperthyroidism*, the facies continually reflect astonishment—staring facies. This is brought about by protruding eyeballs, which bare more than normal proportions of the whites of the eyes; the eyebrows may be lifted; the skin of the face may be flushed and moist. In *shaking palsy*, the face may be so motionless as to appear neatly starched, but accompanying this there may be tremors of the entire head with eyes wide open and the eyeballs in motion. Such an expression in this disease may be accompanied by tremors of the hands or legs and a jumpy speech. In *thyroid deficiency*, the features are thick, coarse, broad. The face is moonlike, expressionless, and stolid; the outer third of the eyebrows may be missing or scanty; the skin is dry. "Pudgy" characterizes these facies. *Cyanotic* facies (cyanosis elsewhere mentioned) may arise from several industrial causes, as well as non-industrial. In either instance, the ears, lips, cheeks will take on a bluish-purple tinge which frequently also may be observed at the finger tips. Some clearly indicative facies scarcely lend themselves to verbal presentation. Thus, the chronic alcoholic reveals his intemperance by his little-describable physiognomy; so also the facies of early tuberculous meningitis, which is unlikely to be seen in industry. Of interest ordinarily limited to the physician are the revealing facies of complex central nervous system diseases, such as myasthenia, dyspituitarism, acromegaly, lenticular degeneration, etc. It is obvious that not in all and every case of the several states or diseases mentioned will the facies be so characteristic as here mentioned, which by design attempt to portray well-established conditions.

CHAPTER XVI—SECTION ONE

Fire and Explosion Hazards of Combustible Gases and Vapors*

G. W. JONES

Fires and explosions resulting from the presence of combustible gases and vapors are among the major hazards in present industrial operations. There is need for a greater appreciation of these hazards and better understanding of means of mitigating and preventing them.

I. Limits of Flammability

Confusion has arisen regarding the meaning of the terms "explosive limits," "flammable limits," and "limits of flammability." In the final analysis these different expressions mean the same thing. Some authorities regard explosive limits as those limiting mixtures within which flame will propagate through the entire volume of the mixture and develop appreciable pressure, while flammable limits, or limits of flammability, are regarded as those limiting mixtures within which flame will propagate entirely through the mixture without regard as to whether pressure is produced.

It is impossible to distinguish a flammation from an explosion by the amount of violence produced. Mixtures just within the limits of flammability, if confined in a long tube and tested by opening one end and igniting at this open end, will propagate flame quietly and slowly through the tube (usually at a uniform speed) and the speed, for a given concentration of combustibles in air, will vary with the direction of flame propagation. This mixture, if confined in a closed bomb of adequate dimensions and ignited when the gases are in motion or gentle turbulence, will propagate flame at a speed several times as fast as that in the open tube and develop pressures ranging up to 30 p.s.i. or more. Thus it is seen that the pressure developed by a flammable mixture depends upon the environment and direction of flame propagation; therefore, no differentiation should, or can, be made between explosive limits and limits of flammability.

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* From the Central Experiment Station, Bureau of Mines, U. S. Department of the Interior, Pittsburgh, Penna.; revised November 15, 1954.

A. FACTORS AFFECTING THE LIMITS OF FLAMMABILITY

Only a brief discussion of the various factors affecting the limits of flammability will be given. A more complete discussion is given in published reports.[1-3] The limits are affected by the direction of flame propagation; the shape, diameter, and length of the test apparatus; the temperature and pressure of the mixture at the time of ignition; the percentage of water vapor present; and, indirectly, by the source of ignition.

Wider limits are obtained for upward propagation of flame than for horizontal or downward propagation. Therefore, the risk of an explosion is greater when the mixtures are ignited from below than when ignited from above.

The limits of flammability are widened as the diameter of the apparatus is increased, rapidly at first and then more slowly as the diameter approaches 2 inches. An apparatus greater than 2 inches in diameter gives limits very little different from those obtained with 2-inch apparatus for tests at atmospheric pressure. The apparatus must be long enough to insure continued propagation of flame after the heat imparted to the mixture by the source of ignition has been dissipated. An apparatus 4 feet or more in length is sufficient. It has been found that if the apparatus is closed when the mixtures are ignited and the gases are in gentle turbulence, the lower limit is reduced slightly.[4]

Ordinary variations of laboratory temperatures have no appreciable effect on the limits of flammability. Elevated temperatures cause a widening of the limits. Normal variations of atmospheric pressure have no appreciable effect on the limits. The effect of high pressures on the limits is neither simple nor uniform, but specific for each particular combustible. As yet, no means has been developed for predicting the effect of high pressures on the limits of flammability for any given combustible in air or oxygen. In certain instances both limits are raised, while in others the limits are narrowed. However, increased pressure widens the limits of flammability of saturated hydrocarbons.[5,6]

The normal quantity of water vapor present in atmospheres at laboratory temperatures affects the lower limit of flammability only to a slight extent. The presence of water vapor reduces the upper limit because some of the oxygen in the mixture is displaced by the water vapor. Since the oxygen concentration is the important factor in an upper-limit mixture, as the oxygen is lowered the amount of combustible that can be burned is decreased, and so the limit is lowered.

[1] H. F. Coward, C. Carpenter, and W. Payman, *J. Chem. Soc.*, **115**, 27 (1919).

[2] H. F. Coward and G. W. Jones, *U. S. Bur. Mines Bull.* No. **503**, 1952.

[3] H. F. Coward, G. W. Jones, C. G. Dunkle, and B. E. Hess, *Mining Met. Invest., Carnegie Inst. Technol. Co-op. Bull.* No. **30**, 1926.

[4] G. W. Jones, E. S. Harris, and W. E. Miller, *U. S. Bur. Mines Tech. Paper* No. **544**, 1933.

[5] G. W. Jones and R. E. Kennedy, *U. S. Bur. Mines Rept. Invest.* No. **3798**, 1945.

[6] G. W. Jones, R. E. Kennedy, and I. Spolan, *U. S. Bur. Mines Rept. Invest.* No. **4557**, 1949.

B. LIMITS OF FLAMMABILITY OF GASES AND VAPORS IN AIR

Industrial safety requires that only those values for the limits of flammability of gases and vapors in air be employed that have been obtained in apparatus giving the widest limits. These conditions are met by the apparatus developed by the United States Bureau of Mines and shown in Figure 1. It is specially designed for determining limits of gases, and vapors of liquids that are volatile enough at laboratory temperatures to give flammable mixtures. In Figure 1, *a* is the glass tube in which the mixture is tested. Its lower end is closed by a lightly lubricated ground-glass plate *b* sealed with mercury *c*. It is evacuated by a pump through the tube *j*. The vapor under test is drawn from its liquid in the container *p*, in amount measured by the manometer *k*. Air or other "atmosphere" is then admitted through the drying tube *q* until atmospheric pressure is reached. The air and vapor are then thoroughly mixed by circulation, by raising and lowering mercury vessel *g* repeatedly for 10 to 30 minutes, depending upon the density of the added combustible vapor. The mercury seal is then removed, glass plate *b*

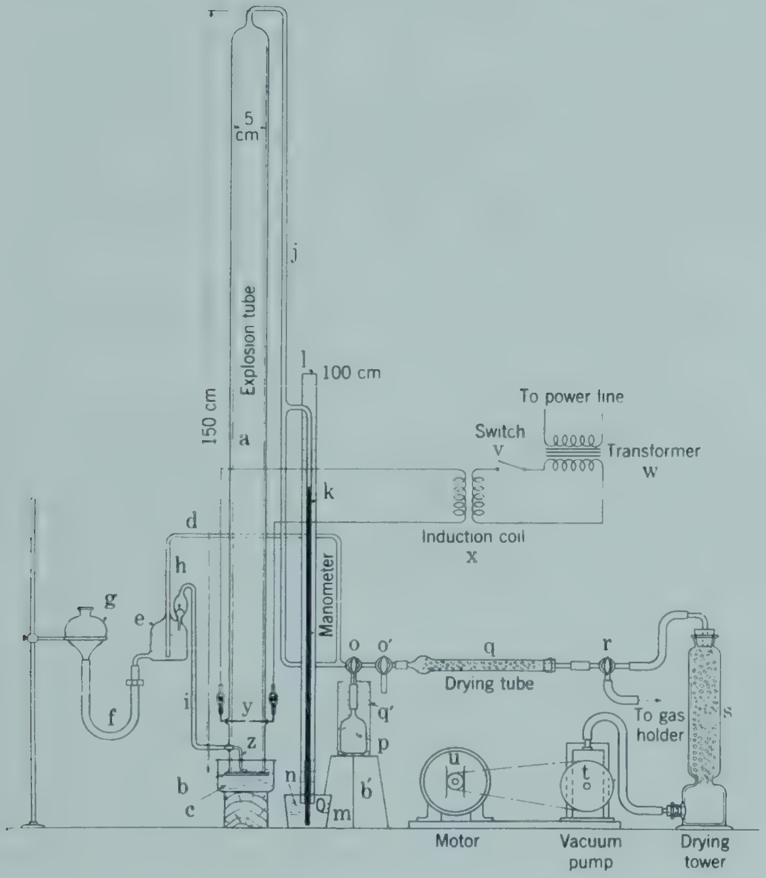

Figure 1. Apparatus for determining the limits of flammability of gases and vapors. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

is slid off the tube, and the flammability of the mixture is tested by sparking at y or by passing a small flame across the open end of the tube.

Most of the values given in Table 1 were obtained by using an apparatus of the type described above and for upward propagation of flame. Values obtained in unusually small apparatus and those in which the direction of flame propagation was other than upward have not been included, except where no other values were available. In some instances values reported by several investigators were found to be in good agreement; however, only one reference has been given. Column (*1*) gives the name; (*2*), the formula; (*3*), the lower limit of flammability; (*4*), the upper limit of flammability; (*5*), the percentage of combustible required for theoretical complete combustion in air; (*6*), the ratio of the lower limit of flammability to the percentage required for theoretical complete combustion; and (*7*), a similar ratio for the upper limit of flammability.

C. CALCULATION OF LIMITS OF FLAMMABILITY

1. One Combustible

Burgess and Wheeler[58] first showed that there is a definite relationship between the calorific value of the combustible and its lower limit of flammability. The calorific values of the pure paraffin hydrocarbons multiplied by their lower limits of flammability gave a constant; that is, on combustion a lower-limit mixture of any of the paraffin hydrocarbons with air liberates the same amount of heat.

Later Thornton[59] announced that the upper limit bears a direct relation to the amount of oxygen needed for theoretical complete combustion. He stated that for the paraffins the upper-limit mixture contained twice as great a volume of gas as the mixture for theoretical complete combustion; acetylene and carbon disulfide, three times the volume; hydrogen, four times the volume; and carbon monoxide, six times the volume. Lower-limit mixtures that just failed to propagate flame contained twice the volume of oxygen needed for theoretical complete combustion of the paraffin mixtures, and thrice the volume for mixtures of other gases. The values given in columns (*6*) and (*7*) of Table 1 show that some of the predictions made by Thornton are approximately correct, while in other cases there are extremely wide variations. The classification is not nearly so simple as Thornton predicted.

If the combustibles are classified according to types, as is done in Table 1, the relationships between the limits and the oxygen required for theoretical complete combustion show better agreement. For the lower limits the average ratio for a given type may be used to predict the limits of compounds for which limits of flammability have not been determined.

TABLE 1

Limits of Flammability of Gases and Vapors in Air

Name (*1*)	Formula (*2*)	Limits of flammability (per cent by volume) Lower (*3*)	Ref. no.	Upper (*4*)	Ref. no.	Per cent by volume combustibles in air. Mixture for theoretical complete combustion (*5*)	Ratio of lower limit to P.C.C.[a] (Column *3* ÷ *5*) (*6*)	Ratio of upper limit to P.C.C.[a] (Column *4* ÷ *5*) (*7*)
		Paraffin hydrocarbons						
Methane	CH_4	5.00	2	15.00	2	9.47	0.53	1.58
Ethane	C_2H_6	3.10	2	12.45	3	5.64	0.55	2.21
Propane	C_3H_8	2.10	7	9.50	3	4.02	0.52	2.36
Butane	C_4H_{10}	1.86	3	8.41	3	3.12	0.60	2.70
Isobutane	C_4H_{10}	1.83	8	8.43	2	3.12	0.59	2.70
Pentane	C_5H_{12}	1.42	2	7.80	2	2.55	0.56	3.06
Isopentane	C_5H_{12}	1.35	2	7.60	2	2.55	0.53	2.98
2,2-Dimethylpropane	C_5H_{12}	1.38	2	7.50	2	2.55	0.54	2.94
Hexane	C_6H_{14}	1.18	2	7.43	2	2.16	0.55	3.44
2,2-Dimethylbutane	C_6H_{14}	1.20	2	7.00	2	2.16	0.56	3.24
2,3-Dimethylbutane	C_6H_{14}	1.20	2	7.00	2	2.16	0.56	3.24
2-Methylpentane	C_6H_{14}	1.18	2	6.95	2	2.16	0.55	3.22
Heptane	C_7H_{16}	1.10	2	6.70	2	1.87	0.59	3.58
2,3-Dimethylpentane	C_7H_{16}	1.12	2	6.75	2	1.87	0.60	3.61
Octane	C_8H_{18}	0.96*	9	4.66*	10	1.65	0.58	2.82
Isooctane	C_8H_{18}	1.00*	9	6.03*	10	1.65	0.61	3.65
2-Methylheptane	C_8H_{18}	0.98*	9	—		1.65	0.59	—
Nonane	C_9H_{20}	0.85*	9	—		1.47	0.58	—
2,3,3,3-Tetramethylpentane	C_9H_{20}	0.77*	10	4.90*	10	1.47	0.52	3.33
3,3-Diethylpentane	C_9H_{20}	0.74*	10	5.75*	10	1.47	0.50	3.91
Decane	$C_{10}H_{22}$	0.77*	10	5.35	10	1.33	0.58	4.02
Dodecane	$C_{12}H_{26}$	0.60*	9	—		1.12	0.54	—
Tetradecane	$C_{14}H_{30}$	0.50*	11	—		0.96	0.52	—
		Olefins						
Ethylene	C_2H_4	2.75	12	28.60	12	6.52	0.42	4.39
Propylene	C_3H_6	2.40	13	10.30	13	4.44	0.54	2.32
Butadiene	C_4H_6	2.00	14	11.50	14	3.67	0.54	3.13
Butylene	C_4H_8	1.98	2	9.65	2	3.37	0.59	2.86
Butene-1	C_4H_8	1.65	2	9.35	2	3.37	0.49	2.77
Butene-2	C_4H_8	1.85	2	9.70	2	3.37	0.55	2.88
Isobutylene	C_4H_8	1.78	2	8.85	2	3.37	0.53	2.63
β-*n*-Amylene	C_5H_{10}	1.50	2	8.70	2	2.72	0.55	3.20
3-Methylbutene-1	C_5H_{10}	1.50	2	9.10	2	2.72	0.55	3.35
		Acetylenes						
Acetylene	C_2H_2	2.50	2	80.50	15	7.72	0.32	10.43
Allylene	C_3H_4	1.74	11	—		4.97	0.35	—
		Aromatics						
Benzene	C_6H_6	1.35	10	7.90*	16	2.72	0.50	2.90
Toluene	C_7H_8	1.17*	16	7.10*	16	2.27	0.52	3.13
Styrene	C_8H_8	1.10*	17	6.10*	17	2.05	0.54	2.98

(*continued*)

TABLE 1 (*continued*)

Name (*1*)	Formula (*2*)	Limits of flammability (per cent by volume) Lower (*3*)	Ref. no.	Upper (*4*)	Ref. no.	Per cent by volume combustibles in air. Mixture for theoretical complete combustion (*5*)	Ratio of lower limit to P.C.C.[a] (Column *3* ÷ *5*) (*6*)	Ratio of upper limit to P.C.C.[a] (Column *4* ÷ *5*) (*7*)
Ethylbenzene	C_8H_{10}	0.99*	16	6.70*	16	1.95	0.51	3.44
o-Xylene	C_8H_{10}	1.09*	16	6.40*	16	1.95	0.56	3.28
m-Xylene	C_8H_{10}	1.09*	16	6.40*	16	1.95	0.56	3.28
p-Xylene	C_8H_{10}	1.08*	16	6.60*	16	1.95	0.55	3.38
Cumene	C_9H_{12}	0.88*	16	6.50*	16	1.71	0.52	3.80
p-Cumene	C_9H_{12}	0.85*	16	5.50*	16	1.71	0.50	3.22
Naphthalene	$C_{10}H_8$	0.88*	18	5.90*	18	1.71	0.52	3.45
Anthracene	$C_{14}H_{10}$	0.63*	11	—		1.25	0.50	—
Cyclic hydrocarbons								
Cyclopropane	C_3H_6	2.45	19	10.45	19	4.44	0.55	2.25
Cyclohexene	C_6H_{10}	1.22*	20	4.81*	20	2.40	0.51	2.00
Cyclohexane	C_6H_{12}	1.33*	2	8.35*	2	2.27	0.59	3.68
Ethylcyclobutane	C_6H_{12}	1.24*	2	7.74*	2	2.27	0.55	3.41
Methylcyclohexane	C_7H_{14}	1.15*	2	—		1.95	0.59	—
Ethylcyclopentane	C_7H_{14}	1.10*	10	6.70*	10	1.95	0.56	3.44
Ethylcyclohexane	C_8H_{16}	0.95*	10	6.60*	10	1.71	0.56	3.86
Turpenes								
Turpentine	$C_{10}H_{16}$	0.69*	21	—		1.47	0.47	—
Alcohols								
Methyl alcohol	CH_4O	6.72	2	36.50*	22	12.24	0.55	2.98
Ethyl alcohol	C_2H_6O	3.28	2	18.95*	23	6.52	0.50	2.91
Allyl alcohol	C_3H_6O	2.52	2	18.00*	2	4.97	0.51	3.62
Propylene glycol	$C_3H_8O_2$	2.62*	2	12.55*	2	4.97	0.53	2.53
Propyl alcohol	C_3H_8O	2.15*	2	13.50*	2	4.44	0.48	3.04
Isopropyl alcohol	C_3H_8O	2.02*	24	11.80*	10	4.44	0.45	2.66
Butyl alcohol	$C_4H_{10}O$	1.45	2	11.25*	2	3.37	0.43	3.34
Isobutyl alcohol	$C_4H_{10}O$	1.68	25	—		3.37	0.50	—
Furfural alcohol	$C_5H_6O_2$	1.80*	2	16.30*	2	3.67	0.49	4.44
Amyl alcohol	$C_5H_{12}O$	1.19	25	—		2.72	0.44	—
Isoamyl alcohol	$C_5H_{12}O$	1.20	11	—		2.72	0.44	—
Triethylene glycol	$C_6H_{14}O_4$	0.89*	2	9.20*	2	2.72	0.33	3.39
Aldehydes								
Acetaldehyde	C_2H_4O	3.97	22	57.00*	22	7.72	0.51	7.38
Acrolein	C_3H_4O	2.85	2	30.5	2	5.64	0.51	5.41
Crotonaldehyde	C_4H_6O	2.12	2	15.5*	2	4.02	0.53	3.86
Butyraldehyde	C_4H_8O	2.47	2	—		3.67	0.67	—
Furfural	C_5H_4O	2.10*	26	—		4.02	0.52	—
Paraldehyde	$C_6H_{12}O_3$	1.30	11	—		2.72	0.48	—
Ethers								
Dimethyl ether	C_2H_6O	3.45	27	18.10	27	6.52	0.53	2.78
Methyl ethyl ether	C_3H_8O	2.00	11	10.10	11	4.44	0.45	2.27
Diethyl ether	$C_4H_{10}O$	1.85	12	36.50	12	3.37	0.55	10.83

TABLE 1 (*continued*)

		Limits of flammability (per cent by volume)				Per cent by volume combustibles in air. Mixture for theoretical complete combustion	Ratio of lower limit to P.C.C.^{a} (Column *3* ÷ *5*)	Ratio of upper limit to P.C.C.^{a} (Column *4* ÷ *5*)
Name (*1*)	Formula (*2*)	Lower (*3*)	Ref. no.	Upper (*4*)	Ref. no.	(*5*)	(*6*)	(*7*)
Ethyl propyl ether	$C_5H_{12}O$	1.90	28	24.00	28	2.72	0.70	8.82
Divinyl ether	C_4H_6O	1.70	29	27.00	29	4.02	0.42	6.72
Isopropyl ether	$C_6H_{14}O$	1.38	2	7.90	2	2.27	0.61	3.48
Methylal	$C_3H_8O_2$	2.95	30	17.40	30	4.97	0.59	3.50
		Ketones						
Acetone	C_3H_6O	2.55	4	12.80	4	4.97	0.51	2.58
Methyl ethyl ketone	C_4H_8O	2.05	11	11.00	11	3.67	0.56	3.00
Methyl propyl ketone	$C_5H_{10}O$	1.55	2	8.15*	2	2.90	0.53	2.81
Methyl isopropyl ketone	$C_5H_{10}O$	1.79	31	9.02*	31	2.90	0.62	3.11
Methyl butyl ketone	$C_6H_{12}O$	1.22	2	8.00*	2	2.40	0.51	3.33
Methyl isobutyl ketone	$C_6H_{12}O$	1.35	2	7.60*	2	2.40	0.56	3.16
Cyclohexanone	$C_6H_{10}O$	1.11*	32	—		2.55	0.44	—
Isophorone	$C_9H_{14}O$	0.84*	2	3.80*	2	1.71	0.49	2.22
		Acids						
Acetic acid	$C_2H_4O_2$	5.40*	2	16.05*	31	9.47	0.57	1.69
Acetic anhydride	$C_4H_6O_3$	2.90*	31	10.30*	31	4.97	0.58	2.07
Hydrocyanic acid	HCN	5.60	32	40.00	32	14.34	0.39	2.79
		Hydrogen						
Hydrogen	H_2	4.00	33	74.20	34	29.50	0.14	2.52
Deuterium	De	4.90	35	75.00	35	29.50	0.17	2.54
		Esters						
Methyl formate	$C_2H_4O_2$	5.90	30	21.70	30	9.47	0.62	2.29
Ethyl formate	$C_3H_6O_2$	3.15	30	16.40	30	5.64	0.56	2.91
Isopropyl formate	$C_4H_8O_2$	2.45	30	—		4.02	0.61	—
Butyl formate	$C_5H_{10}O_2$	1.73*	2	8.15*	2	3.12	0.55	2.61
Isobutyl formate	$C_5H_{10}O_2$	2.00	30	8.90	30	3.12	0.64	2.85
Methyl acetate	$C_3H_6O_2$	3.85	30	15.20	30	5.64	0.68	2.70
Ethyl acetate	$C_4H_8O_2$	2.18	36	11.40	22	4.02	0.54	2.84
Vinyl acetate	$C_4H_6O_2$	2.65	30	13.35	30	4.44	0.60	3.01
Propyl acetate	$C_5H_{10}O_2$	1.77	2	8.00*	2	3.12	0.57	2.56
Isopropyl acetate	$C_5H_{10}O_2$	1.78	2	7.80*	2	3.12	0.57	2.50
Butyl acetate	$C_6H_{12}O_2$	1.40*	31	8.00*	31	2.55	0.55	3.14
Amyl acetate	$C_7H_{14}O_2$	1.03*	31	7.13*	31	2.16	0.48	3.30
Isoamyl acetate	$C_7H_{14}O_2$	1.16*	31	6.96*	31	2.16	0.54	3.22
Methyl propionate	$C_4H_8O_2$	2.45	2	12.60	2	4.02	0.61	3.13
Ethyl propionate	$C_5H_{10}O_2$	1.85	2	11.05	2	3.12	0.59	3.54
Methyl lactate	$C_4H_8O_2$	2.21*	21	—		4.02	0.55	—
Ethyl lactate	$C_5H_{10}O_2$	1.55*	21	—		3.12	0.50	—
		Nitro compounds						
Ethyl nitrate	$C_2H_5NO_3$	4.00	37	—		10.68	0.37	—
Ethyl nitrite	$C_2H_5NO_2$	3.01	22	50.00	22	8.51	0.35	5.88

(*continued*)

TABLE 1 (*continued*)

Name (*1*)	Formula (*2*)	Limits of flammability (per cent by volume)				Per cent by volume combustibles in air. Mixture for theoretical complete combustion (*5*)	Ratio of lower limit to P.C.C.[a] (Column *3* ÷ *5*) (*6*)	Ratio of upper limit to P.C.C.[a] (Column *4* ÷ *5*) (7)
		Lower (*3*)	Ref. no.	Upper (*4*)	Ref. no.			
Cellosolves								
Methyl cellosolve	$C_3H_8O_2$	2.50*	38	19.80*	38	4.97	0.50	3.98
Methyl cellosolve acetate	$C_5H_{10}O_3$	1.75*	38	8.20*	38	3.37	0.52	2.43
Cellosolve acetate	$C_6H_{12}O_3$	1.71*	11	—		2.72	0.63	—
Oxides								
Carbon monoxide	CO	12.50	1	74.20	34	29.50	0.42	2.52
Ethylene oxide	C_2H_4O	3.00	39	100.00	40	7.72	0.39	12.95
Propylene oxide	C_3H_6O	2.00	41	22.00	41	4.97	0.40	4.43
Trioxane	$C_3H_6O_3$	3.57*	10	28.70*	10	6.52	0.55	4.40
Acetic anhydride	$C_4H_6O_3$	2.90*	31	10.30*	31	4.97	0.58	2.07
Dioxane	$C_4H_8O_2$	1.97*	42	22.25*	42	4.02	0.49	5.53
Diethyl peroxide	$C_4H_{10}O_2$	2.34	23	—		3.67	0.64	—
Acetal	$C_6H_{14}O_2$	1.58	30	10.40	30	2.40	0.66	4.33
Nitrogen compounds								
Ammonia	NH_3	15.50	43	26.60	44	21.82	0.71	1.22
Hydrazine	N_2H_4	4.67*	45	100.00	45	17.30	0.27	5.78
Cyanogen	C_2N_2	6.60	46	42.60	46	9.47	0.70	4.50
Acrylonitrile	C_3H_3N	3.05	47	17.00*	47	5.29	0.58	3.21
Pyridine	C_5H_5N	1.81	22	12.40*	22	3.24	0.56	3.83
Quinoline	C_9H_7N	1.21*	48	—		1.91	0.63	—
Nicotine	$C_{10}H_{14}N_2$	0.75*	49	4.00*	49	1.53	0.49	2.61
Sulfur compounds								
Carbon disulfide	CS_2	1.25	2	50.00	22	6.52	0.19	7.67
Hydrogen sulfide	H_2S	4.30	15	45.50	15	12.24	0.35	3.72
Carbon oxysulfide	COS	11.90	50	28.50	50	12.24	0.97	2.33
Dimethyl sulfide	C_2H_6S	2.25	30	19.70	30	4.44	0.51	4.44
Ethyl mercaptan	C_2H_6S	2.80	51	18.20	51	4.44	0.63	4.10
Amines and imines								
Methylamine	CH_5N	4.95	2	20.75	2	8.51	0.58	2.44
Dimethylamine	C_2H_7N	2.80	2	14.40	2	5.29	0.53	2.72
Trimethylamine	C_3H_9N	2.00	2	11.60	2	3.83	0.52	3.03
Ethylamine	C_2H_7N	3.55	2	13.95	2	5.29	0.67	2.64
Diethylamine	$C_4H_{11}N$	1.77	2	10.10	2	3.01	0.59	3.36
Triethylamine	$C_6H_{15}N$	1.25	2	7.90*	2	2.10	0.60	3.76
Propylamine	C_3H_9N	2.01	2	10.35	2	3.83	0.52	2.70
n-Butylamine	$C_4H_{11}N$	1.70	2	9.75*	2	3.01	0.56	3.24
Allylamine	C_3H_7N	2.20	2	22.05	2	4.22	0.52	5.23
Ethyleneimine	C_2H_5N	3.60	2	45.80	2	6.05	0.60	7.57

TABLE 1 (*continued*)

Name (*1*)	Formula (*2*)	Limits of flammability (per cent by volume)				Per cent by volume combustibles in air. Mixture for theoretical complete combustion (*5*)	Ratio of lower limit to P.C.C.[a] (Column *3* ÷ *5*) (*6*)	Ratio of upper limit to P.C.C.[a] (Column *4* ÷ *5*) (*7*)
		Lower (*3*)	Ref. no.	Upper (*4*)	Ref. no.			
		Halogen derivatives						
Methyl chloride	CH_3Cl	8.25	52	18.70	52	12.24	0.67	1.53
Methyl bromide	CH_3Br	13.50[b]	52	14.50[b]	52	12.24	1.10	1.18
Ethyl chloride	C_2H_5Cl	3.85	30	15.40	30	6.52	0.59	2.36
Ethyl bromide	C_2H_5Br	6.75	52	11.25	52	6.52	1.04	1.73
Ethylene dichloride	$C_2H_4Cl_2$	6.20	53	15.90*	53	7.72	0.80	2.06
Vinyl chloride	C_2H_3Cl	4.00	2	21.70	2	7.72	0.52	2.81
Dichloroethylene	$C_2H_2Cl_2$	9.70	2	12.80	2	9.47	1.02	1.35
Ethylene chlorohydrin	C_2H_5OCl	4.84*	10	15.90*	10	6.52	0.74	2.44
Propyl chloride	C_3H_7Cl	2.60	2	11.10*	2	4.44	0.59	2.50
Propylene dichloride	$C_3H_6Cl_2$	3.40	54	14.50*	54	4.97	0.68	2.92
Allyl chloride	C_3H_5Cl	2.90	30	11.30	30	4.97	0.58	2.27
Allyl bromide	C_3H_5Br	4.35	30	7.25	30	4.97	0.88	1.46
2-Chloropropene	C_3H_5Cl	4.50	28	16.00	28	4.97	0.91	3.22
Chlorobutene	C_4H_7Cl	2.25	2	9.25*	2	3.67	0.61	2.52
n-Butyl chloride	C_4H_9Cl	1.85	2	10.10*	2	3.37	0.55	3.00
Isobutyl chloride	C_4H_9Cl	2.05	2	8.75*	2	3.37	0.61	2.60
Butyl bromide	C_4H_9Br	2.56*	31	6.56*	31	3.37	0.76	1.95
n-Amyl chloride	$C_5H_{11}Cl$	1.60*	2	8.65*	2	2.72	0.59	3.18
tert-Amyl chloride	$C_5H_{11}Cl$	1.50*	2	7.40*	2	2.72	0.55	2.72
Chlorobenzene	C_6H_5Cl	1.35*	2	7.05*	2	2.90	0.47	2.43
Dichlorobenzene	$C_6H_4Cl_2$	2.23*	2	9.19*	2	3.12	0.71	2.95
Benzyl chloride	C_7H_7Cl	1.10*	11	—		2.40	0.46	—
		Mixed combustible gases						
Blast furnace gas		35.0	33	73.5	33			
Carbureted water gas		5.5	2	36.0	2			
Coke oven gas		4.4	2	34.0	2			
Manufactured gas		6.5	4	36.0	4			
Natural gas		3.8–6.5	2	13–17	2			
Natural gas[c]		5.4–21.	55	25–35	55			
Oil gas		4.7	2	33	2			
Producer gas		17–35	2	70–80	2			
Water gas		6–7	2	70–72	2			
		Petroleum products						
Gasoline		1.4–1.6	2	7.4–7.6	2			
Kerosene		0.7*	2	4.80*	2			
Naphtha		0.8–1.0	2	4.85*	2			
Stoddard solvent		0.74*	38	5.6*	38			
		Metallo-organic compounds						
Dimethyldichlorosilane	$C_2H_6SiCl_2$	3.4	56	—		4.97	0.68	—
Methyltrichlorosilane	CH_3SiCl_3	7.6	56	—		6.52	1.17	—
Lead tetramethyl	$C_4H_{12}Pb$	1.8	57	—		2.72	0.66	—
Tin tetramethyl	$C_4H_{12}Sn$	1.9	57	—		2.72	0.70	—

*Determinations made at elevated temperatures.

[a] P.C.C. = per cent combustible in air. Mixture for theoretical complete combustion.

[b] Not flammable unless container is closed.

[c] Natural gas containing large amounts of N_2 and/or CO_2.

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2. Two or More Combustibles

The calculation of the limits of flammability of combustible mixtures from a knowledge of the limits of each combustible and the percentage of each combustible present in the mixture can be done rather accurately for a number of mixtures by applying the so-called "mixture law."

Le Chatelier[25] first applied the law to the limits of flammability of gases. The law states that if we separate limit combustible-air mixtures and mix them, then this mixture will also be a limit mixture. The equation for expressing this law in its simplest useful form is written as follows:

$$L = \frac{100}{\dfrac{P_1}{N_1} + \dfrac{P_2}{N_2} + \dfrac{P_3}{N_3} + \dfrac{P_4}{N_4}}$$

when P_1, P_2, P_3, and P_4 are the proportions of the various combustible gases present in the mixture, free of air and inerts (so that $P_1 + P_2 + P_3 + P_4 = 100$), and N_1, N_2, N_3, and N_4 are the respective lower, or upper, limits of flammability of the combustibles in air, then L is the lower, or upper, limit of flammability of the mixture.

As an example of the application of the method we may take a natural gas of the following composition:

Hydrocarbon	Per cent by volume	Limits of flammability (per cent by volume)	
		Lower	Upper
Methane	80.0	5.00	15.00
Ethane	15.0	3.10	12.45
Propane	4.0	2.10	9.50
Butane	1.0	1.86	8.41

$$\text{Lower limit} = \frac{100}{\dfrac{80.0}{5.00} + \dfrac{15.0}{3.10} + \dfrac{4.0}{2.10} + \dfrac{1.0}{1.86}} = 4.30$$

$$\text{Upper limit} = \frac{100}{\dfrac{80.0}{15.00} + \dfrac{15.0}{12.45} + \dfrac{4.0}{9.50} + \dfrac{1.0}{8.41}} = 14.13$$

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This law has been tested by Coward, Carpenter, and Payman[1] and proved to hold for hydrogen, carbon monoxide, and methane containing no inert gases in normal air. Subsequent tests made with paraffin hydrocarbons in air[3] showed that the law could also be applied to these mixtures. Exceptions have been found in tests made with some flammable gases. White[22] found that the law does not hold strictly for hydrogen-ethylene-air mixtures, acetylene-hydrogen-air mixtures, hydrogen sulfide–methane–air mixtures, and mixtures containing carbon disulfide. In tests on some chlorinated hydrocarbons, Coward and Jones[60] found that the law did not hold for methane-dichloroethylene-air mixtures. It was also found[52] to be only approximately correct for mixtures of methyl and ethyl chlorides. It is therefore apparent that the mixture law, useful when its applicability has been proved, cannot be applied indiscriminately, but must first be proved to hold for the combination of gases under investigation.

Many industrial processes require the use of mixtures of various solvents, and although the limits of flammability of the various individual constituents in the mixture may be known, it is not at all certain what the limits of flammability will be for the various mixtures. Investigations of the lower limits of flammability of various solvent mixtures have shown[36] that where the ratios of lower limits of the individual constituents to the amount of oxygen required for theoretical complete combustion are about the same, the limits of mixtures of the constituents may be determined accurately by calculation. For example, limits may be calculated[26] for mixtures of benzene, furfural, and acetone, which have ratios ranging from 0.50 to 0.53; and mixtures of ethyl acetate, ethyl alcohol, and toluene, whose ratios vary from 0.50 to 0.56, also have been found[36] to give calculated results agreeing closely with experimental results.

To date, the accuracy of the above prediction has been proved only for a limited number of mixtures. As information on the subject is accumulated, the classification of compounds according to the ratios should be of considerable value in predicting and calculating the limits of flammability of mixtures of combustible gases and vapors.

3. Complex Gas Mixtures

It is possible to calculate closely the limits of flammability not only of mixtures of combustible gases and vapors in air but also mixtures containing varying amounts of inert gases and air. The limits of flammability of natural, manufactured, producer, blast-furnace, automobile, and sewage gases when mixed with various proportions of the inert gases present may be calculated from a knowledge of the composition of the gas and the flammability of the various constituents present. The actual procedure is rather long and complicated and tables or graphs are required for ascertaining the limits of the combustible–inert

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[58] M. J. Burgess and R. V. Wheeler, *J. Chem. Soc.*, **99**, 2013 (1911).

[59] W. M. Thornton, *Phil. Mag.*, **33**, 190 (1917).

[60] H. F. Coward and G. W. Jones, *Ind. Eng. Chem.*, **22**, 963 (1930).

gas components. The reader who wishes to make such calculations is referred to published reports on the subject.[2,33,55,61]

D. LIMITS OF FLAMMABILITY OF GASES AND VAPORS IN OXYGEN

In some instances, for example, the compressed-gas industry and in hospitals, the flammability of combustible gases in oxygen is of real importance. Published information on this phase of the subject is limited, and in many cases the values appear to be unreliable. A compilation of the best available information on the limits in oxygen is given in Table 2.

TABLE 2

Limits of Flammability of Gases and Vapors in Oxygen

		Limits of flammability (per cent by volume)			
Name	Formula	Lower	Ref. no.	Upper	Ref. no.
Acetaldehyde	C_2H_4O	4.00	2	93.0	2
Acetylene	C_2H_2	2.80	62	93.0	63
Ammonia	NH_3	14.80	44	79.0	44
Benzene	C_6H_6	2.80	64	29.9	64
Butane	C_4H_{10}	1.85	2	49.0	2
Isobutane	C_4H_{10}	1.80	2	48.0	2
Butene-1	C_4H_8	1.75	10	58.3	10
Butene-2	C_4H_8	1.75	10	55.0	10
Carbon monoxide	CO	15.50	65	93.9	65
2-Chloropropene	C_3H_5Cl	4.50	28	54.0	28
Isocrotyl bromide	C_4H_7Br	6.40	28	50.0	28
Isocrotyl chloride	C_4H_7Cl	2.80	28	66.0	28
Cyclopropane	C_3H_6	2.48	19	60.0	19
Deuterium	De	4.90	35	94.7	35
Dichloroethylene	$C_2H_2Cl_2$	10.00	28	26.0	28
Diethyl ether	$C_4H_{10}O$	2.10	66	82.0	12
Dimethyl ether	C_2H_6O	3.90	67	61.4	67
Divinyl ether	C_4H_6O	1.85	29	85.5	29
Ethane	C_2H_6	3.05	2	66.0	2
Ethyl bromide	C_2H_5Br	6.70	28	44.0	28
Ethyl chloride	C_2H_5Cl	4.05	68	67.2	68
Ethylene	C_2H_4	2.90	68	79.9	68
Ethyl-*n*-propyl ether	$C_5H_{10}O$	2.00	28	78.0	28
Hydrogen	H_2	4.65	2	93.9	2
Methane	CH_4	5.15	2	60.5	2
Methyl bromide	CH_3Br	14.00	28	19.0	28
Methyl chloride	CH_3Cl	8.20	69	65.8	69
Methylene chloride	CH_2Cl_2	15.50	70	66.4	70
Propane	C_3H_8	2.25	2	52.0	2
Propylene	C_3H_6	2.10	71	52.8	71
Isopropyl ether	$C_6H_{12}O$	2.20	28	69.0	28
Trichloroethylene	C_2HCl_3	10.30*	72	64.5*	72
Vinyl chloride	C_2H_3Cl	4.00	28	70.0	28

*Determinations made at elevated temperatures.

II. Ignition Temperatures

Before an explosive mixture can propagate flame a portion of the mixture must be heated to its ignition temperature. The ignition temperature may be defined as the minimum temperature at which rapid combustion becomes independent of external supplies of heat. This implies that in order to initiate flame a definite minimum volume of the gaseous mixture must be heated to its ignition temperature and held at this temperature for a sufficient time to enable flame to propagate away from the ignition source. The time period at the ignition temperature necessary to cause the propagation of flame varies over wide limits. For a gas such as hydrogen the time period, or so-called "lag," may be only a fraction of a second, while for ethane the time period may be 100 seconds or longer. It is therefore apparent that, although the temperature at which a given mixture will ignite and burst into flame is very important, the "lag" at the ignition temperature also must be considered, because it often happens that an ignition source may be adequate as far as the temperature is concerned, yet the duration is so short that the ignition source is incapable of initiating a self-propagating flame and the mixture fails to ignite.

A. FACTORS AFFECTING IGNITION TEMPERATURE

The investigation of ignition temperatures is extremely complicated, and the results obtained by various investigators may show wide disagreement because of different experimental conditions. Some of the major factors that affect the ignition temperatures are: the percentage of combustible in the mixture; the "lag," or time required at a given temperature to cause ignition; the percentage of oxygen present; the size, shape, and composition of the apparatus used; the pressure on the experimental mixture at the time of ignition; and the presence or absence of impurities and catalysts in the mixture.

On the basis of the above discussion it becomes apparent that the term "ignition temperature" is not a true physical constant, and reported values for a given combustible may vary widely.

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[70] G. W. Jones, R. E. Kennedy, and F. E. Scott, *U. S. Bur. Mines Rept. Invest.* No. **3737**, 1943.

[71] G. W. Jones and R. E. Kennedy, *Current Researches in Anesthesia and Analgesia*, **9**, 6 (1930).

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B. MINIMUM IGNITION TEMPERATURES OF GASES AND VAPORS

The values tabulated in Table 3 may be termed minimum ignition temperatures of gases and vapors in air. In those instances where numerous values have

TABLE 3

Minimum Ignition Temperatures and Flash Points of Combustible Liquids, Gases, and Vapors

		Ignition temperatures			Flash points		
Name	Formula	° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Acetal	$C_6H_{14}O_2$	446	230	73	97	37	10
Acetaldehyde	C_2H_4O	349	176	74	−36	−38	11
Acetanilide	C_8H_9NO	1017	547	75	345	174	11
Acetic acid	$C_2H_4O_2$	1022	550	73	104	40	11
Acetic anhydride	$C_4H_6O_3$	738	392	76	127	53	32
Acetone	C_3H_6O	1042	561	77	0	−18	11
Acetophenone	C_8H_8O	1060	571	75	221	105	11
Acetyl acetone	$C_5H_8O_2$	644	340	75	174	79	11
Acetyl chloride	C_2H_3OCl	734	390	75	40	4	11
Acetylene	C_2H_2	581	305	78	—	—	
Acrolein	C_3H_4O	453	234	30	<0	<−18	79
Acrylonitrile	C_3H_3N	898	481	47	23	−5	10
Adipic acid	$C_6H_{10}O_4$	792	422	75	385	196	11
Aldol	$C_4H_8O_2$	478	248	75	181	83	11
Allyl alcohol	C_3H_6O	712	378	80	72	22	10
Allylamine	C_3H_7N	705	374	30	—	—	
Allyl bromide	C_3H_5Br	583	295	30	—	—	
Allyl chloride	C_3H_5Cl	909	487	73	−25	−32	79
o-Aminodiphenyl	$C_{12}H_{11}N$	846	452	75	—	—	
Ammonia	NH_3	1204	651	81	—	—	
Amyl acetate	$C_7H_{14}O_2$	676	358	10	77	25	32
Isoamyl acetate	$C_7H_{14}O_2$	680	360	21	77	25	11
Amyl alcohol	$C_5H_{12}O$	572	300	75	100	38	32
tri-Isoamyl alcohol	$C_5H_{12}O$	657	347	75	109	42	11
tert-Amyl alcohol	$C_5H_{12}O$	819	437	75	67	19	11
Amylbenzene	$C_{11}H_{16}$	491*	255*	82	150	66	11
Amyl chloride	$C_5H_{11}Cl$	498	259	73	55	13	11
tert-Amyl chloride	$C_5H_{11}Cl$	649	343	30	10	−12	31
Amylene (*n* and β)	C_5H_{10}	524	273	42	0	−18	11
Amyl ether	$C_{10}H_{22}O$	340	171	75	135	57	11
Isoamyl ether	$C_{10}H_{22}O$	802	428	83	—	—	
Amyl nitrate	$C_5H_{11}NO_3$	381	194	38	—	—	
Amyl nitrite	$C_5H_{11}NO_2$	408	209	75	—	—	
Amyl propionate	$C_8H_{16}O_2$	712	378	75	106	41	11
Aniline	C_6H_7N	1143	617	75	168	76	11
Anthracene	$C_{14}H_{10}$	1004	540	75	250	121	11
Benzaldehyde	C_7H_6O	378	192	32	148	64	32
Benzene	C_6H_6	1044	562	75	12	−11	11
Benzoic acid	$C_7H_6O_2$	1064	573	73	250	121	84
Benzyl acetate	$C_9H_{10}O_2$	860	460	80	216	102	11

(*continued*)

TABLE 3 (*continued*)

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Benzyl alcohol	C_7H_8O	802	428	80	213	101	11
Benzyl benzoate	$C_{14}H_{12}O_2$	898	481	75	298	148	11
Benzyl chloride	C_7H_7Cl	1085	585	75	140	60	11
Bromobenzene	C_6H_5Br	1051	566	75	149	65	85
1,3-Butadiene	C_4H_6	784	418	73	—	—	
Butane	C_4H_{10}	761	405	75	—	—	
Isobutane	C_4H_{10}	864	462	10	—	—	
Butene-1	C_4H_8	723	384	10	—	—	
Butene-2	C_4H_8	615	324	10	—	—	
Butyl acetate	$C_6H_{12}O_2$	790	421	80	72	22	11
Isobutyl acetate	$C_6H_{12}O_2$	793	423	75	64	18	11
Butyl alcohol	$C_4H_{10}O$	653	345	80	84	29	11
Isobutyl alcohol	$C_4H_{10}O$	813	434	80	82	28	85
sec-Butyl alcohol	$C_4H_{10}O$	763	406	75	70	21	10
tert-Butyl alcohol	$C_4H_{10}O$	892	478	73	52	11	10
Butylamine	$C_4H_{11}N$	594	312	31	45	8	79
Isobutylamine	$C_4H_{11}N$	712	378	75	15	−9	79
Butylbenzene	$C_{10}H_{14}$	774	412	75	—	—	
Isobutylbenzene	$C_{10}H_{14}$	802	428	75	—	—	
sec-Butylbenzene	$C_{10}H_{14}$	784	418	75	126	52	11
tert-Butylbenzene	$C_{10}H_{14}$	842	450	75	—	—	
Butyl bromide	C_4H_9Br	509	265	75	55	13	11
Butyl carbitol	$C_8H_{18}O_3$	442	228	11	172	78	11
Butyl cellosolve	$C_6H_{14}O_2$	473	245	38	141	61	11
Butyl chloride	C_4H_9Cl	860	460	73	−18	−28	31
Butylene	C_4H_8	829	443	42	—	—	
Isobutylene	C_4H_8	869	465	75	—	—	
Butyl formate	$C_5H_{10}O_2$	633	334	31	64	18	85
Di-*tert*-butyl peroxide	$C_8H_{18}O_2$	324	162	87	—	—	
Butyl propionate	$C_7H_{14}O_2$	799	426	80	90	32	11
Butyl stearate	$C_{22}H_{44}O_2$	671	355	75	320	160	11
Butyraldehyde	C_4H_8O	446	230	73	−1	−18	10
Butyric acid	$C_4H_8O_2$	846	452	75	170	77	11
Carbon disulfide	CS_2	248	120	88	−22	−30	11
Carbon monoxide	CO	1130	610	89	—	—	
Carbon oxysulfide	COS	318*	159*	90	—	—	
Cellosolve	$C_4H_{10}O_2$	460	238	11	104	40	11
Cellosolve acetate	$C_6H_{12}O_3$	715	379	11	124	51	11
Chlorobenzene	C_6H_5Cl	1180	638	75	85	29	91
o-Cresol	C_7H_8O	1110	599	83	178	81	85
m-Cresol	C_7H_8O	1159	626	83	187	86	85
m-*p*-Cresol	C_7H_8O	1038	559	21	187	86	85
Croton aldehyde	C_4H_6O	450	232	42	55	13	11
Cumene	C_9H_{12}	795	424	75	102	39	79
Cyanamide	CN_2H_2	—	—		285	141	11
Cyanogen	C_2N_2	1562	850	92	—	—	
Cyclohexane	C_6H_{12}	500	260	75	1	−17	11
Cyclohexanol	$C_6H_{12}O$	572	300	75	154	68	11

TABLE 3 (*continued*)

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Cyclohexanone	C_6H_8O	847	453	21	147	64	11
Cyclohexone	$C_6H_{10}O$	788	420	75	—	—	
Cyclohexyl acetate	$C_8H_{14}O_2$	633	334	75	—	—	
Cyclopropane	C_3H_6	928	498	68	—	—	
p-Cymene	$C_{10}H_{14}$	817	436	75	117	47	11
Decalin	$C_{10}H_{18}$	504	262	11	136	58	11
Decane	$C_{10}H_{22}$	406	208	75	115	46	11
Di-isobutyl carbinol	$C_9H_{20}O$	561	294	87	—	—	
Di-isobutyl ketone	$C_9H_{18}O$	730	388	87	118	48	87
o-Dichlorobenzene	$C_6H_4Cl_2$	1198	648	31	151	66	31
1,2-Dichloro-*n*-butane	$C_4H_8Cl_2$	529	276	73	126	52	79
sec-Dichloroethylene	$C_2H_2Cl_2$	826	441	73	57	14	11
Dichloroethyl ether	$C_4H_8OCl_2$	696	369	11	131	55	11
Diethanolamine	$C_4H_{11}NO_2$	1224	662	11	280	138	11
Diethylamine	$C_4H_{11}N$	594	312	31	<0	<−18	79
1,4-Diethylbenzene	$C_{10}H_{14}$	806	430	75	—	—	
Diethylene glycol	$C_4H_{10}O_3$	444	229	11	255	124	11
Diethyl ketone	$C_5H_{10}O$	846	452	75	—	—	
3,3-Diethylpentane	C_9H_{20}	554	290	75	—	—	
Diethyl peroxide	$C_4H_{10}O_2$	372	189	93	—	—	
Dimethylamine	C_2H_7N	756	402	73	—	—	
Dimethyl aniline	$C_8H_{11}N$	700	371	11	145	63	11
2,2-Dimethylbutane	C_6H_{14}	797	425	30	—	—	
2,3-Dimethylbutane	C_6H_{14}	788	420	73	<−20	<−29	79
Dimethyl ether	C_2H_6O	662	350	73	−42	−41	11
Dimethyl formamide	C_3H_7NO	815	435	38	135	57	31
2,3-Dimethylhexane	C_8H_{18}	820	438	94	—	—	
2,3-Dimethylpentane	C_7H_{16}	639	337	30	—	—	
2,2-Dimethylpropane	C_5H_{12}	842	450	30	—	—	
Dimethyl sulfide	C_2H_6S	403	206	31	—	—	
1,1-Dinitrocyclohexane	$C_6H_{10}N_2O_4$	568	298	31	—	—	
2,2-Dinitropropane	$C_3H_6N_2O_4$	554	290	31	—	—	
Dioxane	$C_4H_8O_2$	511	266	42	54	12	95
Dipentene	$C_{10}H_{16}$	459	237	38	113	45	31
Diphenyl	$C_{12}H_{10}$	1051	566	75	235	113	11
Diphenylamine	$C_{12}H_{11}N$	1173	634	75	307	153	11
Diphenyl ether	$C_{12}H_{10}O$	1144	618	75	—	—	
Diphenylmethane	$C_{13}H_{12}$	907	486	75	266	130	11
Divinyl ether	C_4H_6O	680	360	29	—	—	
Dodecane	$C_{12}H_{26}$	399	204	75	165	74	11
Isododecane	$C_{12}H_{26}$	932	500	94	—	—	
Ethane	C_2H_6	959	515	75	—	—	
Ethyl acetate	$C_4H_9O_2$	903	484	80	24	−4	11
Ethyl alcohol	C_2H_6O	738	392	80	55	13	79
Ethylamine	C_2H_7N	723	384	31	<0	<−18	11
Ethyl aniline	$C_8H_{11}N$	894	479	83	185	85	11
Ethylbenzene	C_8H_{10}	810	432	75	64	18	10

(*continued*)

TABLE 3 (*continued*)

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Ethyl bromide	C_2H_5Br	952	511	81	—	—	
Ethyl butyrate	$C_6H_{12}O_2$	865	463	73	78	26	11
Ethyl cellosolve	$C_4H_{10}O_2$	482	250	38	—	—	
Ethyl chloride	C_2H_5Cl	921	494	30	−58	−50	11
Ethyl cyclobutane	C_6H_{12}	414	212	75	—	—	
Ethyl cyclohexane	C_8H_{16}	504	262	75	—	—	
Ethyl cyclopentane	C_7H_{14}	504	262	75	—	—	
Ethylene	C_2H_4	914	490	96	—	—	
Ethylene chlorohydrin	C_2H_5OCl	797	425	73	140	60	11
Ethylene dichloride	$C_2H_4Cl_2$	776	413	11	56	13	11
Ethylene glycol	$C_2H_6O_2$	776	413	80	232	111	11
Ethyleneimine	C_2H_5N	612	322	30	—	—	
Ethylene oxide	C_2H_4O	804	429	11	<0	< −18	11
Ethyl ether	$C_4H_{10}O$	345	174	38	−49	−45	32
Ethyl formate	$C_3H_6O_2$	851	455	75	−4	−20	11
Ethyl lactate	$C_5H_{10}O_3$	752	400	21	115	46	11
Ethyl mercaptan	C_2H_6S	570	299	51	—	—	
Ethyl propionate	$C_5H_{10}O_2$	824	440	38	54	12	11
Formaldehyde	CH_2O	795	424	75	130	54	11
Furfural	$C_5H_4O_2$	736	391	73	140	75	11
Furfural alcohol	$C_5H_6O_2$	736	391	73	167	75	11
Gasoline, regular		536	280	81	−47	−44	81
Gasoline, motor		691	366	38	—	—	
Gasoline, 73 octane		570	299	73	—	—	
Gasoline, 92 octane		734	390	73	—	—	
Gasoline, 100 octane		804	429	73	—	—	
Glycerine	$C_3H_8O_3$	739	393	80	320	160	11
Heptane	C_7H_{16}	433	223	75	25	−4	11
Hexadecane	$C_{16}H_{34}$	401	205	75	—	—	
Hexane	C_6H_{14}	453	234	75	−15	−26	32
Isohexane	C_6H_{14}	543	284	82	< −20	< −29	11
Hexyl alcohol	$C_6H_{14}O$	572	300	82	137	58	11
Hexyl ether	$C_{12}H_{26}O$	369	187	75	170	77	11
Hydrazine	N_2H_4	518	270	45	—	—	
Hydrazine hydrate	N_2H_4-H_2O	558	292	31	—	—	
Hydrogen	H_2	1062	572	97	—	—	
Hydrogen cyanide	HCN	1000	538	11	0	−18	11
Hydrogen sulfide	H_2S	558	292	98	—	—	
Isophorone	C_9H_{14}	864	462	73	184	84	10
Isoprene	C_5H_8	428	220	99	−65	−54	99
Kerosene		444	229	75	100–165	38–74	11
Methane	CH_4	1103	595	97	—	—	
Methyl acetate	$C_3H_6O_2$	936	502	80	14	−10	32
Methylal	$C_3H_8O_2$	459	237	38	0	−18	79
Methyl alcohol	CH_4O	867	464	21	54	12	11
Methyl amine	CH_5N	806	430	10	0	−18	11
Methyl bromide	CH_3Br	999	537	81	—	—	

TABLE 3 (*continued*)

		Ignition temperatures			Flash points		
Name	Formula	° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Methylbutyl ketone	$C_6H_{12}O$	991	533	42	95	35	11
Methyl isobutyl ketone	$C_6H_{12}O$	869	465	30	—	—	
Methyl cellosolve	$C_3H_8O_2$	720	382	38	105	41	79
Methyl chloride	CH_3Cl	1170	632	81	—	—	
Methyl cyclohexane	C_7H_{14}	545*	285*	82	25	−4	11
o-Methylcyclohexanol	$C_7H_{14}O$	565	296	75	154	68	11
p-Methylcyclohexanol	$C_7H_{14}O$	563	295	75	—	—	
Methylene chloride	CH_2Cl_2	1188	642	73	—	—	
Methyl ethyl ketone	C_4H_8O	941	505	21	30	−1	11
Methyl formate	$C_2H_4O_2$	853	456	81	−2	−19	11
Methyl lactate	$C_4H_8O_2$	725	385	21	121	49	11
Methyl naphthalene	$C_{11}H_{10}$	984	529	75	—	—	
2-Methyl pentane	C_6H_{14}	583	306	30	—	—	
2-Methyl propene	C_4H_8	869	465	75	—	—	
Methyl propionate	$C_4H_8O_2$	876	469	30	28	−2	11
Methyl propyl ketone	$C_5H_{10}O$	941	505	42	60	16	11
Methyl salicylate	$C_8H_8O_3$	849	454	32	214	101	11
Naphtha		421–532	216–278	38	20–107	−7–42	11
Naphthalene	$C_{10}H_8$	959	515	100	176	80	95
Neohexane	C_6H_{14}	797	425	30	—	—	
Nicotine	$C_{10}H_{14}N_2$	471	244	49	—	—	
Nitrobenzene	$C_6H_5NO_2$	900	482	32	190	88	11
Nonane	C_9H_{20}	403	206	75	88	31	11
Octane	C_8H_{18}	428	220	75	56	13	11
Isooctane	C_8H_{18}	813	434	10	10	−12	11
Oil, cable impregnating		738	392	31	—	—	
Oil, castor		840	449	11	444	229	11
Oil, cocoanut		—	—		420	216	11
Oil, cod liver		662*	350*	101	—	—	
Oil, corn		740	393	11	490	254	11
Oil, cottonseed		650	343	43	486	252	11
Oil, creosote		637	336	11	165	74	11
Oil, fish		531*	277*	101	420	216	11
Oil, flax		772*	411*	101	—	—	
Oil, gas		640	338	11	150	66	11
Oil, lard		650	343	32	363	184	32
Oil, linseed, raw		650	343	32	432	222	32
Oil, linseed, boiled		650	343	32	403	206	32
Oil, lubricating		711	377	102	—	—	
Oil, lubricating, spindle		478	248	85	169	76	11
Oil, lubricating, turbine		700	371	11	400	204	11
Oil, menhaden		828	442	11	435	224	11
Oil, mineral seal		—	—		170	77	11
Oil, neat's-foot		828	442	11	470	243	11
Oil, olive		650	343	32	437	225	32

(*continued*)

TABLE 3 (*continued*)

		Ignition temperatures			Flash points		
Name	Formula	° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Oil, palm		600	316	32	323	162	32
Oil, paraffin		—	—		444	229	32
Oil, peanut		833	445	11	540	282	11
Oil, pine		—	—		172	78	11
Oil, pine tar		—	—		144	62	11
Oil, rape		836	447	11	325	163	11
Oil, rosin		648	342	11	266	130	11
Oil, soybean		833	445	11	540	282	11
Oil, sperm		586	308	85	428	220	85
Oil, straw		—	—		315	157	85
Oil, tallow		—	—		492	256	11
Oil, transformer		—	—		295	146	11
Oil, tung		855	457	11	552	289	11
Oil, Turkey-red		833	445	11	476	247	11
Oil, whale		800	427	11	446	230	11
Paraffin		473	245	11	390	199	11
Paraldehyde	$C_6H_{12}O_3$	460	238	11	63	17	11
Paraformaldehyde	$C_3H_6O_3$	534	279	87	158	70	11
Pentane	C_5H_{12}	549	287	75	−40	−40	11
Isopentane	C_5H_{12}	788	420	10	<−60	<−51	11
Petroleum ether		550	288	75	−69	−56	11
Phenol	C_6H_6O	1319	715	11	175	79	103
Phthalic anhydride	$C_7H_{14}O_3$	1076	580	38	305	152	11
Pinene	$C_{10}H_{16}$	527*	275*	82	91	33	11
Propane	C_3H_8	920	493	73	—	—	
Propargyl alcohol	C_3H_4O	705	374	87	—	—	
Propyl acetate	$C_5H_{10}O_2$	842	450	73	58	14	11
Isopropyl acetate	$C_5H_{10}O_2$	881	476	10	40	4	85
Propyl alcohol	C_3H_8O	822	439	73	59	15	11
Isopropyl alcohol	C_3H_8O	853	456	80	53	12	11
Propylamine	C_3H_9N	604	318	31	—	—	
Isopropylamine	C_3H_9N	756	402	30	−15	−26	11
Propylbenzene	C_9H_{12}	—	—		86	30	11
Isopropylbenzene	C_9H_{12}	795	424	75	102	39	79
Propyl bromide	C_3H_7Br	914	490	73	—	—	
Propyl chloride	C_3H_7Cl	968	520	73	<0	<−18	11
Propylcyclopentane	C_8H_{16}	545	285	94	—	—	
Propylene	C_3H_6	856	458	42	—	—	
Propylene diamine	$C_3H_{10}N_2$	718	381	87	72	22	87
Propylene dichloride	$C_3H_6Cl_2$	1035	557	54	60	16	54
Propylene glycol	$C_3H_8O_2$	790	421	73	207	97	30
Propylene oxide	C_3H_6O	—	—		−35	−37	79
Propyl ether	$C_6H_{14}O$	372	189	104	—	—	
Isopropyl ether	$C_6H_{14}O$	781	416	10	−18	−28	11
Propyl formate	C_4H_8O	851	455	10	27	−3	11
Iropropyl formate	C_4H_8O	905	485	10	22	−6	10
Propyl nitrate	$C_3H_7NO_3$	379	193	87	—		

TABLE 3 (*continued*)

Name	Formula	Ignition temperatures			Flash points		
		° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Pyridine	C_5H_5N	900	482	32	74	23	32
Stoddard solvent		444	229	75	100–110	38–43	10
Stearic acid	$C_{18}H_{36}O_2$	743	395	11	385	196	11
Styrene	C_8H_8	914	490	73	87	31	10
Tetradecane	$C_{14}H_{30}$	396	202	75	212	100	11
Tetrahydrofurfural alcohol	$C_5H_{10}O_2$	540	282	73	167	75	79
2,2,3,3-Tetramethyl pentane	C_9H_{20}	806	430	75	—	—	
Toluene	C_7H_8	997	536	75	40	4	11
o-Toluidine	C_7H_9N	900	482	32	185	85	11
p-Toluidine	C_7H_9N	900	482	11	188	87	11
Trichloroethylene	C_2HCl_3	865	463	73	—	—	
Triethylamine	$C_6H_{15}N$	450	232	31	20	−7	11
Triethylene glycol	$C_6H_{14}O_4$	700	371	31	350	177	11
Trimethylamine	C_3H_9N	374	190	31	—	—	
Trimethylbenzene	C_9H_{12}	948	509	82	—	—	
2,2,4-Trimethylpentane	C_8H_{18}	813	434	10	10	−12	11
Trioxane	$C_3H_6O_3$	795	424	73	113	45	11
Turpentine	$C_{10}H_{16}$	491	255	21	95	35	11
Valeric acid	$C_5H_{10}O_2$	1274	690	105	—	—	
Valeric aldehyde	$C_5H_{10}O$	608	320	105	—	—	
Vinyl acetate	$C_4H_6O_2$	800	427	11	18	−8	11
o-Xylene	C_8H_{10}	867	464	75	63	17	14
m-Xylene	C_8H_{10}	982	528	75	77	25	79
p-Xylene	C_8H_{10}	984	529	75	77	25	79
o-Xylidine	$C_8H_{11}N$	—	—		206	97	11

* Determinations made in oxygen.

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been reported, the lowest apparently reliable one has been taken, after due consideration has been given to the size of the apparatus, the composition of the surface that came into contact with the heated mixture, and the method used to determine the ignition temperatures.

C. IGNITION TEMPERATURES IN AIR AND OXYGEN

From an industrial standpoint the minimum ignition temperatures of combustibles in air are what is desired, although occasionally their ignition temperatures in pure oxygen are desired. It is also of interest to compare the ignition temperatures of combustibles in both air and oxygen, since numerous references dealing with ignition temperatures have reported results in which the ignition temperatures in oxygen were sometimes higher than in air. Such reported results appear very unusual because combustibles heated in pure oxygen to reaction temperatures should react and oxidize at a higher rate and therefore ignite at a lower temperature in oxygen than in air.

The results given in Table 4, based on studies that were carried out under similar conditions, prove rather conclusively that combustibles have lower ignition temperatures in oxygen than in air.

III. Flash Points

The flash point may be defined as the minimum temperature at which a liquid gives off vapor sufficient to form a flammable mixture in contact with air. It is a rather rough yet quick way of measuring the relative combustibility of volatile liquids and, in turn, determines the approximate temperature below which combustibles may be stored and used without creating explosive atmospheres. In general, the higher the flash point of a liquid, the greater its safety in respect to fires and explosions. It should be emphasized, however, that the flash point alone

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TABLE 4

Ignition Temperatures of Combustible Gases and Vapors in Air and Oxygen

		Minimum ignition temperatures					
		In air			In oxygen		
Name	Formula	° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Acetal	$C_6H_{14}O_2$	446	230	73	345	174	73
Acetaldehyde	C_2H_4O	349	176	74	221	105	74
Acetic acid	$C_2H_4O_2$	1022	550	73	914	490	73
Acetic anhydride	$C_4H_6O_3$	738	392	76	682	361	76
Acetone	C_3H_6O	1042	561	77	905	485	73
Acrolein	C_3H_4O	453	234	30	439	226	30
Acrylonitrile	C_3H_3N	898	481	47	860	460	47
Allyl alcohol	C_3H_6O	712	378	80	658	348	73
Allylamine	C_3H_7N	705	374	30	586	308	30
Allyl bromide	C_3H_5Br	583	295	30	516	269	30
Allyl chloride	C_3H_5Cl	909	487	73	759	404	73
Amyl acetate	$C_7H_{14}O_2$	676	358	10	453	234	10
Benzoic acid	$C_7H_6O_2$	1064	573	73	1033	556	73
Benzyl alcohol	C_7H_8O	802	428	80	704	373	82
1,3-Butadiene	C_4H_6	784	418	73	635	335	73
Butane	C_4H_{10}	761	405	75	542	283	73
Isobutane	C_4H_{10}	864	462	10	606	319	10
Butene-1	C_4H_8	723	384	10	590	310	10
Butyl alcohol	$C_4H_{10}O$	653	345	80	622	328	82
Isobutyl alcohol	$C_4H_{10}O$	813	434	80	687	364	86
sec-Butyl alcohol	$C_4H_{10}O$	763	406	75	711	377	73
tert-Butyl alcohol	$C_4H_{10}O$	892	478	73	860	460	73
Butylamine	$C_4H_{11}N$	594	312	31	536	280	31
Isobutylamine	$C_4H_{11}N$	712	378	75	626	330	10
Butylbenzene	$C_{10}H_{14}$	774	412	75	527	275	30
Isobutylbenzene	$C_{10}H_{14}$	802	428	75	588	309	30
sec-Butylbenzene	$C_{10}H_{14}$	784	418	75	700	371	30
Butyl formate	$C_5H_{10}O_2$	633	334	31	540	282	31
Butyraldehyde	C_4H_8O	446	230	73	403	206	73
Carbon disulfide	CS_2	248	120	88	225	107	88
Carbon monoxide	CO	1130	610	89	1090	588	106
Cyanogen	C_2N_2	1562	850	92	1492	811	92
Cyclohexane	C_6H_{12}	500	260	75	489	254	30
Cyclopropane	C_3H_6	928	498	68	849	454	68
Decane	$C_{10}H_{22}$	406	208	75	396	202	30
o-Dichlorobenzene	$C_6H_4Cl_2$	1198	648	31	1123	606	31
1,2-Dichloro-*n*-butane	$C_4H_8Cl_2$	529	276	73	482	250	73
Diethylamine	$C_4H_{11}N$	594	312	31	554	290	31
1,4-Diethylbenzene	$C_{10}H_{14}$	806	430	75	590	310	38
3,3-Diethylpentane	C_9H_{20}	554	290	75	432	222	38
Dimethylamine	C_2H_7N	756	402	73	655	346	73
2,2-Dimethylbutane	C_6H_{14}	797	425	30	520	271	30
2,3-Dimethylbutane	C_6H_{14}	788	420	73	568	298	73

(continued)

TABLE 4 (*continued*)

Name	Formula	Minimum ignition temperatures					
		In air			In oxygen		
		° F.	° C.	Ref. no.	° F.	° C.	Ref. no.
Dimethyl ether	C_2H_6O	662	350	73	468	252	73
2,3-Dimethylpentane	C_7H_{16}	639	337	30	495	257	30
2,2-Dimethylpropane	C_5H_{12}	842	450	30	552	289	30
Dimethyl sulfide	C_2H_6S	403	206	31	374	190	31
Divinyl ether	C_4H_6O	680	360	29	331	166	30
Ethane	C_2H_6	959	515	75	943	506	10
Ethyl alcohol	C_2H_6O	738	392	80	624	329	82
Ethylamine	C_2H_7N	723	384	31	633	334	31
Ethyl butyrate	$C_6H_{12}O_2$	865	463	73	664	351	73
Ethyl chloride	C_2H_5Cl	921	494	30	874	468	73
Ethylcyclobutane	C_6H_{12}	414	212	75	390	199	30
Ethylcyclohexane	C_8H_{16}	504	262	75	487	253	30
Ethylcyclopentane	C_7H_{14}	504	262	75	462	242	30
Ethylene	C_2H_4	914	490	96	905	485	96
Ethylenechlorohydrin	C_2H_5OCl	797	425	73	752	400	73
Ethyleneimine	C_2H_5N	612	322	30	559	293	30
Ethyl ether	$C_4H_{10}O$	345	174	38	336	169	38
Ethyl mercaptan	C_2H_6S	570	299	51	502	261	51
Ethyl propionate	$C_5H_{10}O_2$	824	440	38	601	316	38
Furfural alcohol	$C_5H_6O_2$	736	391	73	687	364	73
Gasoline, motor		691	366	38	500	260	38
Heptane	C_7H_{16}	433	223	75	408	209	38
Hexane	C_6H_{14}	453	234	75	437	225	38
Hydrazine	N_2H_4	518	270	45	399	204	45
Hydrazine hydrate	N_2H_4-H_2O	558	292	31	424	218	31
Hydrogen	H_2	1062	572	97	1067	575	97
Hydrogen sulfide	H_2S	558	292	98	428	220	92
Isophorone	$C_9H_{14}O$	864	462	73	612	322	73
Methane	CH_4	1103	595	97	1033	556	92
Methyl alcohol	CH_4O	867	464	21	862	461	73
Methylamine	CH_5N	806	430	10	752	400	10
Methyl isobutyl ketone	$C_6H_{12}O$	869	465	30	541	283	30
Methylene chloride	CH_2Cl_2	1188	642	73	1123	606	73
2-Methylpentane	C_6H_{14}	583	306	30	464	240	30
Methyl propionate	$C_4H_8O_2$	876	469	30	804	429	30
Naphthalene	$C_{10}H_8$	959	515	100	918	492	100
Neohexane	C_6H_{14}	797	425	30	520	271	30
Nicotine	$C_{10}H_{14}N_2$	471	244	49	455	235	49
Octane	C_8H_{18}	428	220	75	406	208	73
Isooctane	C_8H_{18}	813	434	10	541	283	10
Paraldehyde	$C_6H_{12}O_3$	460	238	11	410	210	82
Pentane	C_5H_{12}	549	287	75	496	258	73
Isopentane	C_5H_{12}	788	420	10	561	294	10
Phthalic anhydride	$C_7H_4O_3$	1076	580	38	1033	556	38

TABLE 4 (*continued*)

Name	Formula	Minimum ignition temperature: In air ° F.	° C.	Ref. no.	In oxygen ° F.	° C.	Ref. no.
Propane	C_3H_8	920	493	73	874	468	73
Propyl acetate	$C_5H_{10}O_2$	842	450	73	730	388	73
Isopropyl acetate	$C_5H_{10}O_2$	881	476	10	838	448	73
Propyl alcohol	C_3H_8O	822	439	73	622	328	86
Propylamine	C_3H_9N	604	318	31	540	282	31
Isopropylamine	C_3H_9N	756	402	30	698	370	30
Propyl bromide	C_3H_7Br	914	490	73	491	255	73
Propylene	C_3H_6	856	458	42	793	423	30
Propylene glycol	$C_3H_8O_2$	790	421	73	738	392	73
Isopropyl ether	$C_6H_{14}O$	781	416	10	306	152	10
Propyl formate	C_4H_8O	851	455	10	594	312	10
Isopropyl formate	C_4H_8O	905	485	10	774	412	10
Styrene	C_8H_8	914	490	73	842	450	73
Trichloroethylene	C_2HCl_3	865	463	73	786	419	73
Triethylamine	$C_6H_{15}N$	450	232	31	388	198	31
Triethylene glycol	$C_6H_{14}O_4$	700	371	31	471	244	31
Trimethylamine	C_3H_9N	374	190	31	347	175	31
2,2,4-Trimethylpentane	C_8H_{18}	813	434	10	542	283	10
Turpentine	$C_{10}H_{12}$	491	255	21	464	240	107

is not the only measure of the fire and explosion hazards. Other important factors, such as its minimum ignition temperature, flammable limits, temperature range of flammability, density of the vapor, and chemical stability, are also of marked importance.

The flash point is determined by "closed"- or "open"-cup methods. In either case a given volume of the liquid is heated in a container at a definite rate, and periodically a test flame or spark is passed across the surface of the liquid. The temperature at which, on ignition, a flame passes across the surface of the liquid in the container is taken as the flash point. The container is open to the air in the open-cup method, while in the closed-cup method the space above the liquid is covered. A small opening is uncovered only at the time the test flame is introduced. Lower values are obtained by the closed-cup method and it gives more accurate indications of flammable-vapor hazards for a given temperature. The flash points tabulated in Table 3 are for the closed-cup method.

IV. Temperature Range of Flammability

Combustible gases, such as methane, hydrogen, and acetylene, when mixed with air in explosive proportions, are but slightly affected as to explosion hazards

[106] K. Bunte and A. Block, *Gas- u. Wasserfach,* **78,** 325 (1935).

[107] H. Moore, *J. Soc. Chem. Ind.* (*London*), **36,** 109 (1917).

by moderate changes in temperature. With combustible liquids, on the other hand, a small change in temperature may cause a marked difference as to their explosion hazards. This is especially important for combustible liquids having vapor pressures that will give flammable vapor-air mixtures at or near ordinary room temperatures. The vapor pressure of a liquid may be such that at, say, 80° F., its vapor pressure is too low to give flammable mixtures with air, yet when heated a few degrees above this temperature it will liberate sufficient vapor to create flammable mixtures.

The United States Bureau of Mines has designed and uses an apparatus, shown in Figure 2 that determines the temperature range over which a given combustible liquid is able to give flammable mixtures in air saturated with the combustible vapor. Explosion tube *d* is 2.5 cm. in diameter and 20 cm. in length. Platinum electrodes *e* are employed to ignite the mixtures. Sparks generated by transformer *m* and induction coil *n* are passed across electrodes *e* when a test for explosibility of the atmosphere in the tube is desired. Contacts between the electrodes and induction coil *n* are made through mercury seals *h* and *h'*. The explosion tube *d* is immersed in a liquid bath (alcohol, water, or mineral seal oil depending on the temperature required), kept at a uniform temperature by stirrer *l*, and heated to a desired temperature by an electric heater *b*. A thermometer *k* is employed for indicating the temperature of the bath.

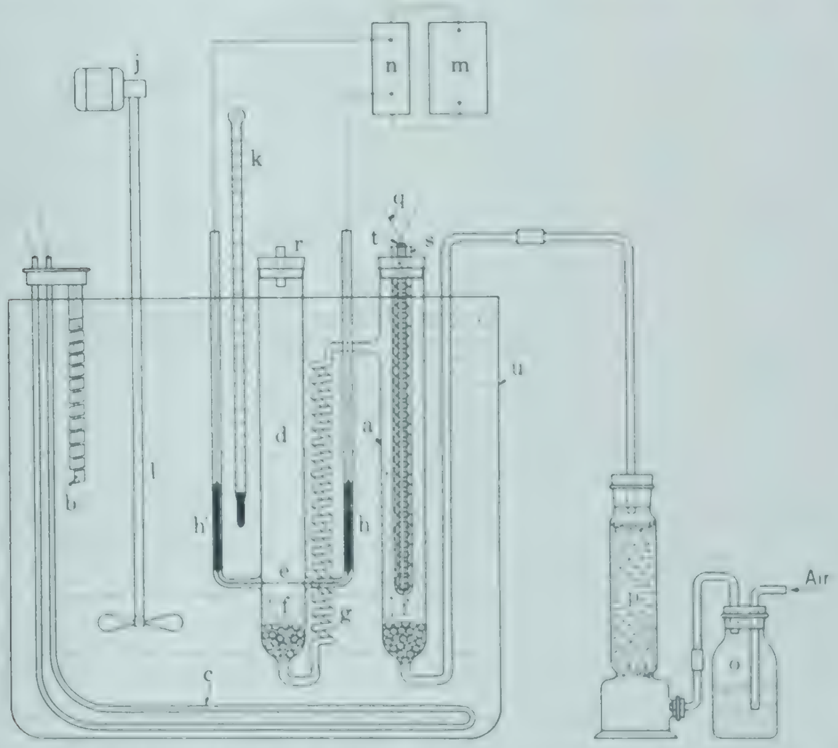

Figure 2. Apparatus for determining the limits of flammability of a volatile liquid. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

To determine the temperature range over which a combustible liquid gives flammable mixtures, the combustible liquid is poured into *d* until the level is 2 cm. below the electrodes; cork *r*, which has an opening in its center, is placed in the top of explosion tube *d*. Air is turned on and adjusted to flow at the rate of 2 liters per hour as indicated by bubbler *o*. The air then passes through tower *p* containing a drying agent, and thence through glass coil *g* in the bath to bring the air to the temperature of the bath before it passes through the combustible liquid into explosion tube *d*. Air is passed through the liquid at the above rate for 10 minutes at a given temperature, and then a test for flammability is made by loosening cork *r* and causing sparks to pass across electrodes *e*. If the combustible liquid gives a flammable mixture with air at the temperature tested, flame will pass up the tube and out the top. Tests are continued by the method of trial and error until a minimum temperature is obtained at which flame carries from the electrodes upward through the tube. The temperature of the bath is then raised, and the temperature at which the upper limit is reached is ascertained in a similar manner.

From a practical standpoint, the temperature range of flammability means that if the combustible liquid is stored or used at temperatures below the minimum temperature given above, flammable mixtures with air cannot be obtained. However, as soon as the minimum temperature is exceeded, flammable mixtures are created if air is saturated with the combustible vapor liberated by the liquid, and such saturated air continues to be flammable until the upper temperature value is reached. At this temperature the percentage of vapor in air saturated with the vapor liberated by the liquid becomes so high that the mixture is incapable of propagating flame. It should be noted that mixtures of air saturated with vapor at the upper temperature limit or higher, although not flammable per se, do become flammable when additional air is added.

The temperature range of flammability for typical combustible liquids is given in Table 5. The flash points also are given so that comparison may be made with the lower temperature limit.

In the tests made in the apparatus shown in Figure 2, flame is propagated upward, and the vapor-air mixture is maintained at the same temperature as the combustible liquid. Under these conditions, lower temperatures should be obtained than those in standard closed-cup flash-point testing apparatus, since in the latter the vapor is not uniformly mixed with the air at the time of ignition, the mixture is ignited from above so that the propagating flame travels horizontally and downward, and for combustible liquids having flash points above normal room temperature the vapor-air mixture is at a lower temperature than that of the liquid. These factors tend to give flash points that are some degrees higher than the minimum temperature at which the liquid may liberate combustible vapor in amounts sufficient to create flammable mixtures in contact with air.

The fact that the flash points of all the combustible liquids listed in Table 5 are higher than the minimum temperature of flammability bears out this con-

TABLE 5

Temperature Range of Flammability and Flash Points of Typical Combustible Liquids

Name	Formula	Boiling point (° C.)	Flash point		Temperature range of flammability			
					Lower		Upper	
			° F.	° C.	° F.	° C.	° F.	° C.
Acetic acid	$C_2H_4O_2$	118.1	104	40	99	37.3	136	57.9
Acetone	C_3H_6O	56.5	0	−18	−4	−20.0	41	5.0
Acrylonitrile	C_3H_3N	76.0	23	−5	21	−6.2	85	29.4
Allyl alcohol	C_3H_6O	96.6	72	22	66	19.0	138	58.8
Amyl chloride	$C_5H_{11}Cl$	106.6	73	55	42	5.5	104	40.0
Butyl iodide	C_4H_9I	129.6	—	—	92	33.5	126	52.0
Chlorobutene	C_4H_7Cl	67.0	0	−18	−9	−23.0	40	4.5
Crotonaldehyde	C_4H_6O	104.0	55	13	47	8.5	113	45.0
Dioxane	$C_4H_8O_2$	101.0	54	12	47	8.5	137	58.5
Ethylene dichloride	$C_2H_4Cl_2$	84.0	56	13	52	11.0	93	34.0
Furfural	$C_5H_4O_2$	161.0	140	60	133	56.0	237	114.0
Methyl alcohol	CH_4O	66.0	54	12	46	8.0	99	37.0
Methyl Cellosolve	$C_3H_8O_2$	124.5	105	41	93	34.0	176	80.0
Methyl butyl ketone	$C_6H_{12}O$	127.0	95	35	72	22.5	139	59.5
Naphtha		Variable	101	38	98	37.0	163	72.8
Propylene dichloride	$C_3H_6Cl_2$	96.8	61	16	52	11.0	97	36.0
Propylene glycol	$C_3H_8O_2$	188.0	207	97	205	96.0	266	130.0

clusion. In some cases the difference amounts to 15 to 20° F., and in others it is somewhat less. The practical significance of these results is that the flash point does not give the absolute minimum temperature at which flammable mixtures may be produced. To be sure that the liquid will not create flammable atmospheres in contact with air, a temperature varying from 5 to 20° F. below the flash point must not be exceeded.

V. Methods of Minimizing Explosions

A. CONTROL OF THE OXYGEN CONTENT OF THE ATMOSPHERE

The fact that a combustible gas, vapor, or mist will not burn or explode when the oxygen content of the atmosphere is reduced below a certain definite value, varying with the combustible material under consideration, enables one to definitely control and in many cases actually eliminate explosion hazards.

The oxygen present in an explosive atmosphere may be reduced by direct absorption, using special reagents and catalysts, or by dilution with inert gases, such as nitrogen, carbon dioxide, or combinations of these inerts, as represented by flue gas or exhaust gas from internal-combustion engines. Automobile exhaust gas and flue gases, made by burning fuel gas or fuel oil with the proper pro-

TABLE 6

Oxygen Values below Which Flames of Combustible Gases and Vapors are Extinguished

Name	Formula	Oxygen percentage below which no mixture is flammable			
		Nitrogen as diluent in air	Ref. no.	Carbon dioxide as diluent in air	Ref. no.
Methane	CH_4	12.1	108	14.6	108
Ethane	C_2H_6	11.0	109	13.4	109
Propane	C_3H_8	11.4	55	14.3	55
Butane	C_4H_{10}	12.1	55	14.5	55
Isobutane	C_4H_{10}	12.0	8	14.8	8
Pentane	C_5H_{12}	12.1	110	14.4	110
Isopentane	C_5H_{12}	12.1	30	14.6	30
Hexane	C_6H_{14}	11.9	110	14.5	110
2,2-Dimethylbutane	C_6H_{14}	12.1	30	14.7	30
Heptane	C_7H_{16}	11.6	30	14.2	30
Natural gas		12.0	111	14.4	111
Gasoline		11.6	112	14.4	112
Ethylene	C_2H_4	10.0	71	11.7	71
Propylene	C_3H_6	11.5	13	14.1	13
Butene-1	C_4H_8	11.4	30	13.9	30
Butene-2	C_4H_8	11.7	30	14.0	30
Isobutylene	C_4H_8	12.1	30	14.8	30
3-Methylbutene-1	C_5H_{10}	11.4	30	13.9	30
1,3-Butadiene	C_4H_6	10.4	111	13.1	111
Benzene	C_6H_6	11.2	113	13.9	113
Cyclopropane	C_3H_6	11.7	19	13.9	19
Methyl alcohol	CH_4O	9.7	30	11.9	30
Ethyl alcohol	C_2H_6O	10.6	30	13.0	30
Dimethyl ether	C_2H_6O	10.3	30	13.1	30
Diethyl ether	$C_4H_{10}O$	10.3	30	13.2	30
Acetone	C_3H_6O	11.6	30	14.3	30
Methylisobutyl ketone	$C_6H_{12}O$	11.4	30	—	
Methyl formate	$C_2H_4O_2$	10.1	30	12.5	30
Ethyl formate	$C_3H_6O_2$	10.4	30	12.8	30
Methyl acetate	$C_3H_6O_2$	10.9	30	13.6	30
Isobutyl formate	$C_5H_{10}O_2$	12.4	30	14.8	30
Methylamine	CH_5N	10.7	30	—	
Allyl chloride	C_3H_5Cl	12.6	30	15.1	30
Hydrogen	H_2	5.0	114	5.9	114
Carbon disulfide	CS_2	5.4	30	7.6	30
Carbon monoxide	CO	5.6	114	5.9	114

[108] H. F. Coward and F. J. Hartwell, *J. Chem. Soc.*, **129**, 1522 (1926).

[109] G. W. Jones and R. E. Kennedy, *U. S. Bur. Mines Rept. Invest.* No. **3172,** 1932.

[110] G. W. Jones and R. E. Kennedy, *Ind. Eng. Chem.*, **27,** 1344 (1935).

[111] G. W. Jones and R. E. Kennedy, *U. S. Bur. Mines Rept. Invest.* No. **3691,** 1943.

[112] G. W. Jones and W. R. Gilliland, *U. S. Bur. Mines Rept. Invest.* No. **3871,** 1946.

[113] G. W. Jones, *U. S. Bur. Mines Rept. Invest.* No. **3787,** 1944.

[114] G. W. Jones and G. St. J. Perrott, *Ind. Eng. Chem.*, **19,** 985 (1927).

portions of air, have low oxygen contents and are especially suited for reducing the oxygen content of atmospheres. Carbon dioxide compressed in cylinders or stored in the liquid state in special holders maintained at low temperatures, dry ice, carbon tetrachloride and Freons (halogenated methane compounds) may also be used for this purpose. It should be remembered that no toxic gas or vapor is suitable for use as a diluent in situations where it may be inhaled; likewise atmospheres deficient in oxygen may not be respirable.

Table 6 shows the critical oxygen values for a number of combustible gases and vapors, below which flames will not propagate or explosions take place when the reduction of the oxygen content is brought about by the addition of nitrogen and the addition of carbon dioxide. The critical oxygen values for any given combustible vary with the concentration of the combustible present; however, the values given in Table 6 are minimum ones and cover any concentrations of the combustible that may be present.

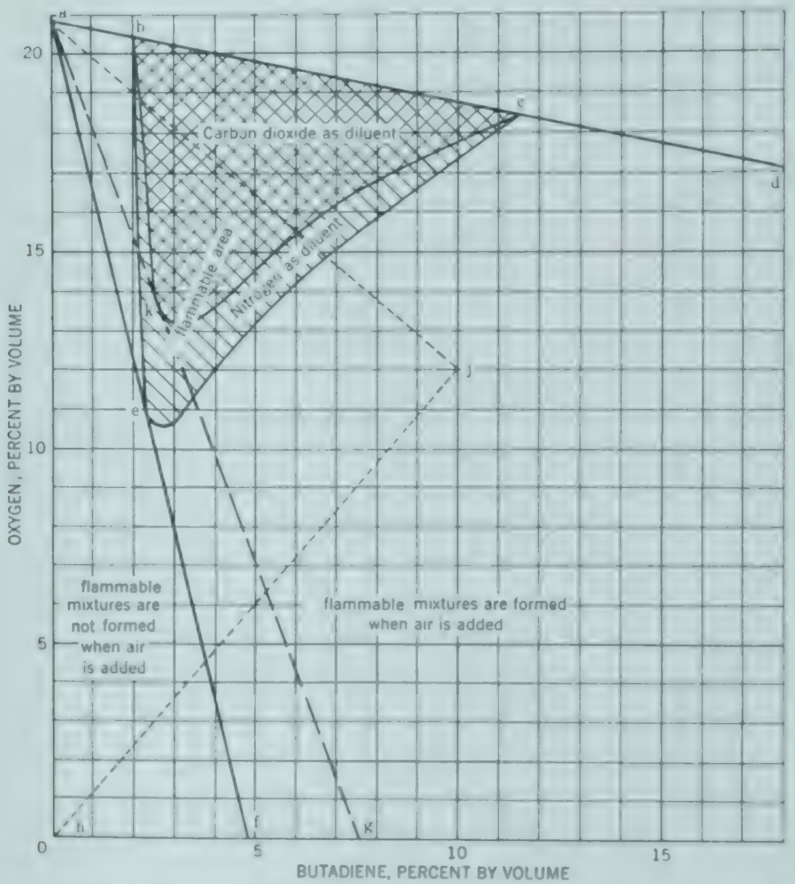

Figure 3. Flammability of butadiene, air, added nitrogen, and added carbon dioxide. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

The relationship between concentration of combustible and the critical oxygen requirements to prevent flame propagation is shown to better advantage by graphs, such as that in Figure 3. This graph shows the flammable areas of all possible mixtures of butadiene, air, and added nitrogen or carbon dioxide. The straight line *ad* represents the composition of mixtures of butadiene and pure air containing up to 18 per cent of butadiene. The flammable limits, shown by the intercept *bc* on this line, are 2.00 per cent for the lower and 11.50 per cent for the upper limit. All mixtures between these limits are flammable. As nitrogen or carbon dioxide is added, the oxygen concentration is lowered and, as shown, the limits are narrowed. Finally, when the oxygen content is reduced to 10.5 per cent, all mixtures of butadiene, air, and added nitrogen become nonflammable. The mixture that will propagate flame with a minimum concentration of oxygen contains 2.60 per cent of butadiene. If the atmosphere contains 5.00 per cent of butadiene the graph shows that the oxygen concentration needs to be reduced to only 13.2 per cent. Although this mixture having 5.00 per cent of butadiene will not propagate flame when the oxygen content is below 13.2 per cent, the graph shows that if air is added to the mixture it becomes flammable, since addition of air shifts the composition of the mixture to the left and toward the point *a* so that the composition passes through a range of mixtures that are flammable.

The usual problem in dealing with combustible mixtures is to control the atmosphere so that the composition at all times is outside the flammable range. An example showing how this may be accomplished is given for butadiene, air, and added nitrogen mixtures. The graph, Figure 3, enables one to determine at a glance the explosion hazards involved. If a particular atmosphere is analyzed and is found to contain, say, 12 per cent of oxygen and 10 per cent of butadiene, as indicated by the point *j* on the graph, this shows at once that the mixture cannot propagate flame until air is added. However, if equipment containing this particular mixture is to be taken out of service and it is desired to do so without the possibilities of explosions, the atmosphere must be altered so as to pass around the flammable area. It becomes necessary to alter the composition of the atmosphere until it falls into the area left of the line *aef*, and in no case should it fall into the flammable area *bec*. The oxygen content must be reduced to some value below 10.5 per cent to pass safely from the composition given by the point *j* to atmospheres of the composition given by any point to the left of the line *aef*. Nitrogen can be added until the oxygen content is reduced to less than 4.6 per cent, thereby shifting the composition along line *jh* and reducing the butadiene content to 3.7 per cent or less; the mixture thus obtained will fall into the area left of the line *aef*. The composition of the atmosphere now is such that it cannot be rendered flammable when air is added, because a line drawn from any point in this area to *a* will not pass through the flammable area. Air can therefore be added to the equipment and the combustibles swept out without danger of explosions. The graph given in Figure 3 applies only for butadiene. Graphs for many other flammable gases and vapors are given in *U. S. Bureau of Mines Bulletin 503.*[2]

B. OPERATING OUTSIDE THE RANGE OF FLAMMABILITY

Processes that necessitate the use of combustible gases or vapors should be carried out, wherever possible, under conditions in which the atmospheres are outside the ranges of flammability of the combustibles used. If possible, the concentrations of combustibles should be kept below their lower limits of flammability, because under these conditions there is no danger of explosions if air finds its way into the mixture. If the concentration of combustibles must be above the lower limit of flammability, it is advisable to raise the concentration until the combustibles present are above the upper limit. No explosion hazard will result while the atmosphere is above the upper limit; the danger arises only when additional air finds its way into the mixture, and this is most likely to occur when the process is started up or closed down.

When combustible liquids are used, the explosion hazards may be controlled by regulation of the temperature so that the vapor pressure will give atmospheres outside the limits of flammability. In applying this method of control, the limits of flammability of the vapor in air, and the vapor pressures of the combustible over the temperature range to be used, must be known; or, by employing the apparatus shown in Figure 2, the temperature range of flammability may be determined directly.

An example of the application of this method in connection with a solvent naphtha is given in Figure 4. The graph shows the vapor pressures of the solvent naphtha at various temperatures. The lower and upper temperature limits of flammability of saturated-air mixtures are shown by the points where the vapor pressure curve crosses the two horizontal lines. The space between the two horizontal lines gives the range of vapor pressures that produce flammable mixtures when air is saturated with the vapor. The temperature range for this particular naphtha was found to be 98 to 164° F. The graph shows that the naphtha does not have enough vapor pressure to create flammable mixtures with air at temperatures below 98° F. Above this temperature, flammable mixtures are produced and continue so until a temperature of 164° F. is reached, when the combustible vapor content of the saturated-air mixtures is so high that flame will no longer propagate through the mixture. It should be noted that combustion could take place above 164° F. if the air were not saturated. The graph shows that, although the naphtha is relatively safe to use at ordinary room temperatures, a slight increase in temperature renders the combustible highly flammable in contact with air.

C. USE OF LESS FLAMMABLE MATERIALS

Wherever possible, combustible liquids with the least flammable characteristics should be employed. Materials should be used that have vapor pressures at the temperature used that give atmospheres not flammable in contact with air. When this cannot be done, the use of chlorinated hydrocarbons should be con-

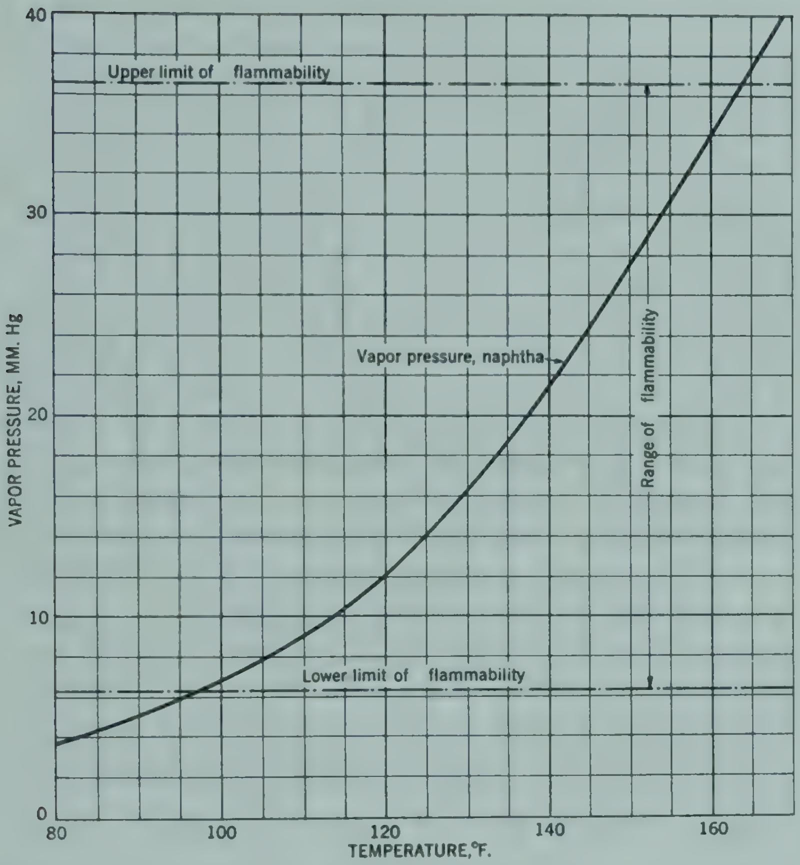

Figure. 4. Relationship between limits of flammability and vapor pressure of a combustible liquid. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

sidered. The degree of flammability of a hydrocarbon is reduced by replacing with halogens one or more of the hydrogen atoms in the compound. Table 7 shows how the flammability of a combustible gas is reduced by successively replacing with chlorine the hydrogen atoms.

TABLE 7

Effect on the Flammability after Substitution of Chlorine Atoms for Hydrogen in Methane

Name	Formula	Flammability	Limits of flammability (per cent by volume)	
			Lower	Upper
Methane	CH_4	Highly flammable	5.00	15.00
Methyl chloride	CH_3Cl	Moderately flammable	8.25	18.70
Methylene chloride	CH_2Cl_2	Not flammable in air at ordinary temperatures		
Chloroform	$CHCl_3$	Not flammable in air or oxygen		
Carbon tetrachloride	CCl_4	Not flammable in air or oxygen		

Methane is highly flammable in air when the concentrations are within the limits given above. Methyl chloride does not produce as violent explosions as certain methane-air mixtures, yet explosions of this combustible in air may do considerable damage. Methylene chloride is entirely safe when mixed with air at ordinary temperatures and pressures, but it is flammable in air at elevated temperatures, and, when mixed with pure oxygen in the right proportions, forms highly explosive mixtures. Chloroform has no explosive properties, while carbon tetrachloride is entirely nonflammable with air or oxygen in any proportions or temperatures and, in fact, is used to good advantage in the preparation of noncombustible, nonflammable dry-cleaning compounds. By the addition of the proper proportions of CCl_4 to combustible liquids, such as naphtha and petroleum distillates, the resulting mixtures are rendered incombustible and nonflammable. However, when these liquid mixtures evaporate, unless the vapor pressure of the combustible portion is as great as that of carbon tetrachloride, flammable liquid mixtures may remain. At least one serious explosion is known to have occurred from such a mixture. Conversely, should the combustible portion have a vapor pressure greater than that of carbon tetrachloride, the liquid residue would remain nonflammable, but flammable vapor-air mixtures could be formed from its evaporation.

Trichloroethylene and various Freon compounds may be used to advantage where liquids having nonflammable characteristics are required.

D. ELIMINATION OF IGNITION SOURCES

Combustible gases and vapors, mixed with air or pure oxygen in proportions to give flammable mixtures, may be employed safely provided all sources of ignition are eliminated. The atmosphere in the gasoline tanks of the millions of automobiles and trucks in use on our streets and highways contains either flammable mixtures or mixtures that become flammable when air is added, yet the number of accidents caused by these conditions is extremely small. This is largely because the tanks are kept closed, the mixtures inside the tanks are usually above the upper limit of flammability, and no sources of ignition are present in the tank or around the filler cap.

The safety engineer is primarily interested in the sources of ignition that may cause explosions. These sources may be classified as given below:

- Ignition sources
  - Flames
    - Open lights
    - Matches and cigarette lighters
    - Fires in boilers and water heaters
    - Burning material; incinerators
  - Sparks
    - Static electricity
    - Electrical shorts and arcs
    - Lightning
    - Sparks from tools
  - Heated materials
    - Glowing metals; hot cinders
    - Overheated bearings
    - Electric light filaments
    - Spontaneous combustion

Most of the sources of ignition given above can be controlled by establishing proper safety regulations and installing flameproof and vaporproof electrical equipment; others, by designing the plants so that boilers, water heaters, incinerators, and other equipment where there are open flames and incandescent materials are installed in other buildings at a safe distance from the place where the processes involving explosion hazards are carried out.

Static electricity has caused many serious fires and explosions and is one of the most difficult ignition hazards to control. There are few operations in which it may not be present. It is more serious in dry atmospheres where the relative humidity is below 50 per cent. Static electricity may be generated by friction, that is, by slipping belts, pulleys, and revolving machinery, and by passage of solids, liquids, or gases at high velocity through small openings. It also may be generated by impact, pressure, cleavage, and induction. It may be partly or totally eliminated by the proper grounding of all machinery, pipes, and other equipment where charges may accumulate. Whenever practical there is added safety in also maintaining the room humidity above 50 per cent.

E. SEGREGATION OF HAZARDOUS OPERATIONS

Operations that, through necessity rather than choice, require the use of large volumes of flammable gases or vapors should be segregated from other operations. This requires installation of hazardous processes in buildings at a safe distance, and, if heavy combustible vapors are involved, the elevation should be below that of other buildings, so that in case of a fire or explosion the liquids and vapors that may be released will not flow toward other adjacent buildings. Tables of safe distance for various operations involving the use of combustible liquids and vapors have not been developed adequately, as has been done in the manufacture and storage of explosives. Therefore, it becomes the duty of the safety engineer to use his own judgment as to what distance is safe for a given operation.

F. PROVISION OF ADEQUATE VENTILATION

The necessity for adequate ventilation where flammable gases and vapors are handled and used cannot be too strongly emphasized. This need for adequate ventilation applies not only to the spaces around the equipment in which the vapors may be present, but also to all conduits, trenches, and tunnels where pipes for conveying flammable gases and vapors and pipelines for conveying flammable liquids are installed. Such lines should be carried in the open air from one building to another, and in buildings they should be suspended above the floor level where they can be inspected readily for leaks.

The buildings should be of light material that will not offer too great resistance to applied pressure if an explosion occurs. The roofs should be provided with ventilators, and windows should be installed with tilting-type sashes that open when pressure is exerted from the inside. A reduction of pressure on the walls of the buildings following an explosion can be obtained by outside glazing and by scoring the glass panes before they are installed.[115]

It is impossible to have too much ventilation around exceedingly hazardous operations. Whenever possible the operations should be carried out entirely in the open air, as is done in certain processes in the petroleum industry, with no closed structures, except those to house instruments and other equipment that must be protected from the weather.

G. RELEASE DIAPHRAGMS AND VENTS

Adequate release diaphragms should be provided on all equipment in which explosive mixtures may be present. The ideal release diaphragm is that having zero mass and infinite area. Although this cannot be realized in practice, the construction and size of release openings should approach the above ideal as closely as possible, yet be strong enough to sustain the operating pressure within the equipment without danger of rupture or leakage, except in case of an explosion within the equipment.

To protect properly a given installation containing explosive mixtures the following major factors must be known or determined experimentally: (*1*) the type and concentration of the combustible vapor or gas that may be present in the equipment; (*2*) the maximum pressure the equipment will safely stand; (*3*) the maximum pressure developed by the mixtures on explosion; (*4*) the area of release openings necessary to keep the pressures below the safe maximum pressure; (*5*) the kind, area, and thickness of the diaphragm material that will rupture at the desired pressure; (*6*) the proper location of the diaphragms to release the pressure developed before excessive pressures are reached. For specific information on this subject the reader is referred to published reports.[115-121] Release diaphragms are now available that will rupture at definite pressures ranging from less than 1 to more than 1000 p.s.i. Various types of materials are used, and they may be obtained with protective coatings where corrosive atmospheres are encountered.

One example of explosive mixtures of acetone and air will be discussed to show how the proper diaphragms may be determined. Figure 5 gives the pressures developed when the area of release opening is varied from no opening to 45 square inches per cubic foot of space in the equipment. These values were obtained experimentally in an 8-liter closed bomb with mixtures containing 5.50 per cent of acetone vapor, a concentration that gives the highest pressure on explosion.

[115] H. R. Brown and R. L. Hanson, *Chem. & Met. Eng.*, **40**, 1030 (1929).

[116] M. E. Bonyun, *Chem. & Met. Eng.*, **42**, 260 (1935).

[117] S. Chester and B. W. Jesser, *Trans. Am. Soc. Mech. Engrs.*, **74**, 229 (1952).

[118] C. E. Huff, *Chem. & Met. Eng.*, **44**, 715 (1937).

[119] G. W. Jones, E. S. Harris, and B. B. Beattie, *U. S. Bur. Mines Tech. Paper* No. **553**, 1933.

[120] G. F. Lake and N. P. Inglis, *Inst. Mech. Engrs. (London)*, **142**, 365 (1940).

[121] T. S. Murphy, *Chem. & Met. Eng.*, **99**, 108 (1944).

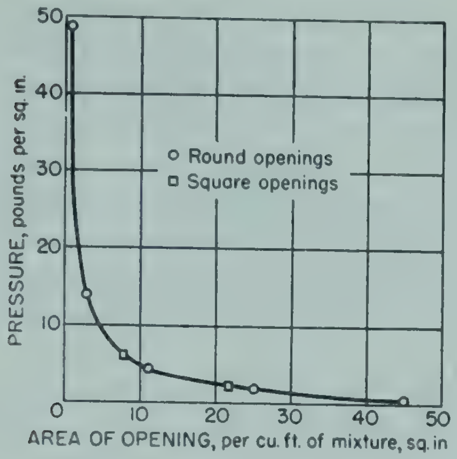

Figure 5. Relation of pressures produced to area of opening, 5.50 per cent acetone-air mixtures (8.05 liter bomb).

Let it be assumed that the equipment should not be subjected to a pressure greater than 10 p.s.i.; then from the results given in Figure 5 the area of release openings should be at least 5 square inches per cubic foot of space.

Next is determination of the proper size and thickness of the diaphragm material that will provide release of the gases from the equipment at a pressure of 10 p.s.i. or less. In general, lead, tin, aluminum, copper, gold, platinum, and special alloys have been found to be most suitable for release materials at low pressures. An example is shown of tests made on aluminum foil of 0.001-inch thickness in an 8-liter bomb using acetone-air mixtures. The rupturing pressures for openings of different sizes and for different concentrations of acetone in air on explosion are given in Figure 6. The rupturing pressures increase as the area of the opening is reduced. In this example, where the pressure must not exceed 10 p.s.i., the curves show that the diaphragms must be at least 3 inches in diameter for this particular aluminum foil; and, as previously determined, the number of release openings should be such as to give 5 square inches of diaphragm release opening per cubic foot of space in the equipment.

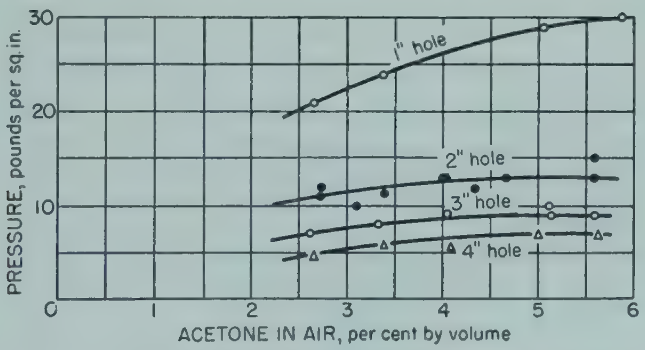

Figure 6. Aluminum diaphragm tests (0.001 inch thick).

The pressure required to rupture a given diaphragm material has been found by experiment [119] to be directly proportional to the ratio of the perimeter to the area. This relation can be expressed by the equation $P = KS/A$ in which P is the pressure, in pounds per square inch, required to rupture the diaphragm, A the area in square inches, S the perimeter in inches, and K a constant characteristic of the particular diaphragm material being used. In practice, K is determined for any given diaphragm material by testing the material in an opening of any given size and determining the pressure required to rupture the diaphragm. The determined value of K can then be used to calculate the rupturing pressure of openings of any size.

The location and spacing of the release diaphragms are very important. Experiments made in round ducts 12 inches in diameter and 15 feet in length with acetone-air mixtures showed that the release diaphragms should be spaced not more than 10 feet apart, and every dead end and sharp bend required a release diaphragm to prevent building up excessive pressures at these points.[119]

H. COMBUSTIBLE GAS INDICATORS FOR FLAMMABLE ATMOSPHERES

Combustible gas indicators or recorders should be installed in all equipment where hazardous concentrations of combustibles may be present. The sampling locations should be chosen so that test mixtures may be taken from different locations. Equipment is available for taking samples periodically from 20 or more locations and recording the concentrations on one chart.

This chapter does not propose to discuss the merits of indicators and recorders. The performance and success of any of these devices can be ascertained only by actual trial under plant operating conditions. They should be calibrated by chemical methods against the particular combustibles used in the process. The temperature of the indicator should be approximately the same as that of the space from which the samples are taken if heavy combustible vapors are being tested. If the space from which the samples are taken is at an elevated temperature, the higher vapor pressure of the combustible at these elevated temperatures will liberate quantities of the vapor into the space, but when samples are withdrawn to a location at a lower temperature, part of the vapor may condense and give misleading results.

Pure gum and similar types of tubing are not satisfactory for sampling heavy hydrocarbon vapors. A 10-foot length of rubber sampling tubing may absorb the greater part of the hydrocarbon vapor present in an atmosphere during its passage through the tubing to the indicator. Copper or other tubing proven to be satisfactory for sampling the gases in question should be used in these instances.

CHAPTER XVI—SECTION TWO

Explosion and Fire Hazards of Combustible Dusts

IRVING HARTMANN

I. The Explosion Hazard

A dust explosion is essentially a very rapid combustion of a cloud or suspension of dust in air, during which heat is generated at a much higher rate than it is dissipated to the surroundings. This phenomenon is characterized by the sudden development of pressure, which frequently causes great destruction of plant and equipment. Generally speaking, any combustible solid material in finely divided form might produce a dust explosion if thrown into suspension in air and ignited. The conditions necessary for the explosion are a sufficiently dense dust cloud; adequate oxygen, air, or other supporter of combustion; and an ignition source intense enough and in contact with the dust long enough to raise the temperature of part of the dust mixture to the ignition point. It should be pointed out that coarse dust particles (in some cases up to 20-mesh or 710-μ size), as well as fine dust, might be involved in an explosion; it should be noted also that the dust concentrations necessary for explosions, of the order of billions of particles per cubic foot, are much higher than those generally considered from a toxicological standpoint.

Tens of thousands of industrial plants in the United States are subject to the hazard of dust explosions. According to published statistics,[1] up to December, 1956, 1120 dust explosions had occurred; 676 persons had been killed, 1770 had been injured, and the estimated property damage was 100 million dollars. The explosions took place in a wide variety of establishments, including grain elevators, woodworking plants, feed and cereal mills, flour mills, sugar refineries, fertilizer plants, malt houses, cotton mills, and plants producing starch and corn products. Others occurred in plants where cork dust, pulverized coal, metal dust, sulfur dust, bark dust, coffee and spice dusts, paper dust, phonograph-record dust, pitch and resin dust, rubber dust, or other combustible dusts were present. Within the last few years very severe explosions, with appreciable loss of life, have occurred in a confectionery plant, a grain elevator, a coal-pulverizing plant, a thermal coal-drying installation, a phenolic-resin plant, and a light-metal finishing shop.

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[1] *Report of Important Dust Explosions.* Natl. Fire Protect. Assoc., Boston, 1957.

Rapid industrial expansion and development of new products have greatly increased the potential explosion hazard in recent years. Examples of new dust-producing industries and of new uses of combustible dusts and powders are manufacture of titanium and other metal powders for varied atomic energy, pyrotechnic, jet propulsion, cutting torches, high explosives of special compositions, powder metallurgy, and other applications; production and use of coal chars; complete gasification of pulverized coal; processing of agricultural residues; manufacture of dehydrated food products; production of chemical catalysts; preparation of new insecticides, antibiotics, and other chemical compounds; development of new synthetic resins and molding compounds; and finishing of plastic automobile bodies.

The following have been established as some of the definite causes of industrial dust explosions: electricity, as sparks from motors, fuses, switches, short circuits, static electrical discharges, and breaking of incandescent lights; frictional sparks from foreign material going through grinding mills and into fans, from sledge hammers, from workmen's shoes, and from grinding wheels and buffers; hot particles, such as glowing material fed to mills or dust collectors and sparks from boilers and from locomotives; heated surfaces, such as overheated bearings, slipping conveyor and other belts, and other moving parts of machines, dust settled on hot light bulbs, dust on steam coils and on hot pipes in driers, dust on overheated electric motors, on starting boxes and other electrical equipment, choke-ups and friction in grain elevators; open flames and lights, such as lanterns, gas lights, torches, matches and smoking, and miscellaneous small fires, including spontaneous ignition of waste and other materials, breaks in oil and fuel lines, and boiler backfires; small explosions of flammable vapors and of dust blown into furnace and incinerator flues; and disturbance of burning dust by use of water hose.

A. FACTORS AFFECTING EXPLOSIBILITY OF DUSTS

Dust explosions are in several respects similar to gas explosions, particularly as the size of the dust particles approaches colloidal dimensions. To produce either type of explosion the combustible must be intimately mixed with the air; generally an external ignition source is needed to initiate the explosions; the mixtures have lower and upper explosive limits, and the explosions of limit mixtures are weak; and both kinds of explosions have an induction or ignition-lag period. The energy released by complete combustion of some flammable dusts in a given volume of air is greater, and therefore the maximum pressures are higher, than is developed in corresponding gas explosions. On the other hand, the rate of pressure rise in gas explosions is usually higher than in dust explosions. Nevertheless dust explosions are frequently more devastating than gas explosions, partly because of the longer duration and greater impulse of dust explosions, and partly because dust is frequently widely distributed, either unavoidably as in coal mines or as a result of lack of proper attention. When this initially dormant dust is dispersed by the first ignition, in some cases a secondary and sometimes even a third explosion of much greater force is produced.

The likelihood of forming an explosive dust cloud depends on the dispersibility of the particles and on their ability to remain in suspension for any length of time. The dust cloud might be formed by a sudden disturbance incident to repair work, a small gas ignition, or some other cause; or the cloud might be an inherent part of the manufacturing process, as within a grinding mill or a pneumatic conveying system. The ignition sensitivity of a dust cloud depends on the ignition temperature and the minimum energy required for ignition. The ignition temperature is not a definite physical constant, characteristic of the dust alone, but its value depends to a degree on the definition adopted and the test equipment and procedure used in its determination. Nevertheless, it has a practical significance. Dusts that have high ignition temperatures and require considerable energy for ignition are less likely to ignite and to produce explosions from accidental causes than are more readily flammable dusts. However, there is little if any relation between the ignition temperature and the minimum igniting energy. The violence of an explosion, as manifested by the maximum pressure and the speed of the explosion, depends on several factors, some of which also affect the ignition temperature and the minimum energy. These include the nature or chemical composition of the dust; its fineness and physical structure; the concentration of the dust cloud; the turbulence of the mixture; the composition of the gaseous atmosphere containing the dust; the nature of the ignition source and its position in the explosion space; and the type, size, strength, vent area, and other properties of the container or structure in which the explosion occurs. A brief discussion of some of these parameters follows.

1. *Composition of Dust*

The ease of oxidation, the oxygen requirement for complete combustion, and the heat of combustion are specific properties of a substance that affect its explosibility. The ease of oxidation influences the ignition temperature as well as the rate of burning. The oxygen requirement determines the dust concentration at which all the dust in a given volume of air will burn. The heat of combustion has a direct bearing on the maximum pressure developed during an explosion, in that the pressure is due partly to the heating of the air and other gases by the heat of combustion of the dust and partly to the formation of gaseous products of combustion. The amount of gas, chiefly nitrogen, remaining after the combustion of aluminum and other metal powders in air is less than the initial volume of air in the combustion space; therefore in this case the pressure developed is due entirely to the expansion of the nitrogen by the available heat. When carbon burns in air, the volume of carbon dioxide and nitrogen after combustion is the same as the volume of air beforehand. On the other hand, when sugar or starch dust burns in air the volume of gaseous combustion products, carbon dioxide, nitrogen, and water vapor, will be greater than the volume of air beforehand.

Since the dust must be heated to its ignition temperature before it ignites, and the combustion products, solid as well as gaseous, are heated during the explosion, the specific heats of these substances also influence the pressure that may be developed. If the temperature of the explosion flame is high enough to cause appreciable dissociation of, say, carbon dioxide, water vapor or other products, this will likewise affect the maximum pressure.

The purity of a dust has an important bearing on its flammability. High percentages of incombustibles, whether inherent in the form of mineral matter, moisture or volatile components, or added inert matter, reduce the ignition sensitivity and the explosion hazard by virtue of their heat-absorbing and possibly inhibiting action.

Many dusts contain volatile combustible matter that is given off below the ignition temperature of the dust. This in general promotes ignition of the dusts and makes them more explosive. The effect is particularly evident with coal dusts (see Figure 1) and with pulverized-fuel-pitch dusts, whose explosibilities vary

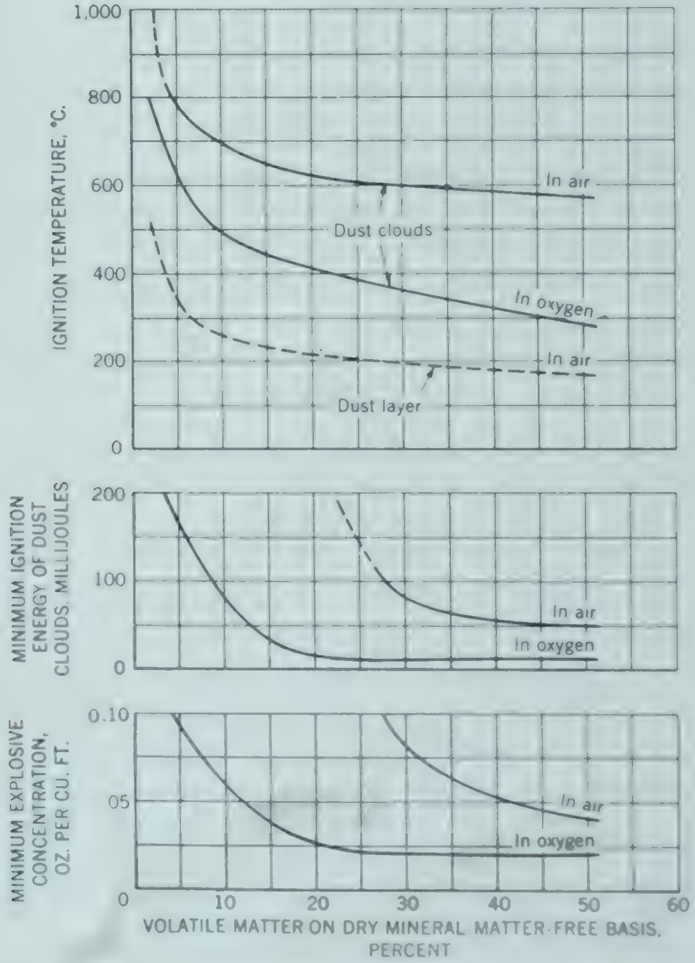

Figure 1. Minimum explosive concentration, minimum igniting energy, and ignition temperature of fine (through No. 200 sieve) coal dusts in air and in oxygen. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

with their volatile contents, as illustrated in papers by Greenwald[2] and Hartmann and co-workers.[3,4] The low volatile content of anthracite is the principal reason for its low explosibility.

The mechanism of ignition of dust particles and flame propagation through dust clouds is not yet fully understood, although definite progress has been made in this direction. According to early views, based largely on observation in coal mines, dust explosions could occur only if the atmosphere contained some flammable gas. Later experience with coal and other organic dusts, which contain combustible volatile matter, led to the so-called predistillation theory of dust ignition. According to this, the ignition source heats the dust particles and causes evolution of volatile matter. This gas mixes with the air and ignites; the energy thus released in turn ignites the solid particles. More modern theory indicates that some combustible dusts vaporize upon heating, and their explosions are essentially homogeneous oxidation reactions, similar to the combustion of premixed gases. The boiling points of these materials are lower than the flame temperatures and their heats of vaporization smaller than the energy needed to initiate rapid surface oxidation. Aluminum, magnesium, and some organic dusts fall into this group. On the other hand, the explosions of other dusts are primarily heterogeneous reactions, coupled with a second-step oxidation in the gas phase; graphite is an example. The reaction rate is governed here by the oxygen diffusion toward the surface of the dust particles.

Some dusts, including metal powders (aluminum, magnesium, iron, lead, thorium, titanium, uranium, zirconium, and others), under certain conditions combine with nitrogen in the air to form nitrides. When this happens during a dust explosion, the heat of formation of the nitride as well as that of the oxide may play a part in determining the maximum pressure that is developed. Furthermore, in such circumstances a higher concentration of dust could be burned in a given volume of air than when only the oxide is formed.

2. Fineness and Physical Structure of Dust

For a number of reasons, the fineness of dust particles has a vital effect on explosibility. Fine dust can be thrown into suspension more readily, it disperses more uniformly and it remains in suspension longer than coarse dust, so that chances for explosions are greater from fine dust. The explosibility of dusts in general increases with decrease in particle size because small dust particles have a greater specific surface, mix better with air, and oxidize more rapidly. Per unit weight of dust, fine particles adsorb more oxygen, their electrical capacitance is higher, and greater electrical charges can develop on their surface. The combined effect of these factors is a lower ignition temperature, lower igniting energy

[2] H. P. Greenwald, *U. S. Bur. Mines Rept. Invest.* No. **3489,** 1940.

[3] I. Hartmann, M. Jacobson, and R. P. Williams, *U. S. Bur. Mines Rept. Invest.* No. **5052,** 1954.

[4] I. Hartmann, H. C. Howarth, and H. P. Greenwald, *U. S. Bur. Mines Tech. Paper* No. **617,** 1940.

(see Figure 2), and lower minimum explosive concentration. Furthermore, since in a fine dust cloud there are more particles with a greater total surface area and the particles are spaced more closely than the particles in a coarse cloud of equal weight concentration, the rate of flame propagation is greater and the heat losses are smaller; therefore in a fine dust cloud higher maximum pressures and higher rates are developed in explosions. These effects are illustrated in several papers by Hartmann and co-workers for coal[3], for metal powders,[5] for synthetic resins and molding compositions,[6] and for cornstarch.[7] An extreme example of the effect of fineness on flammability is manifested by the pyrophoric behavior of certain magnesium, lead, iron, uranium, and other metal powders. When of very small particle size, these powders oxidize so rapidly upon exposure in air that they ignite spontaneously.

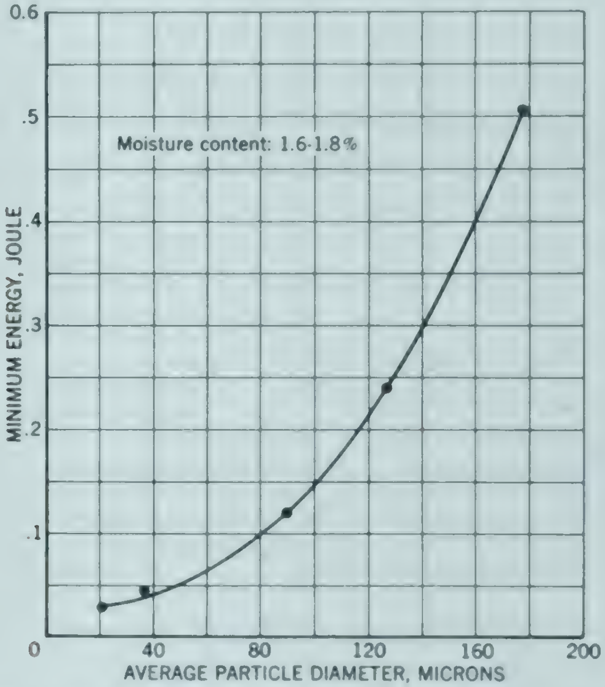

Figure 2. Effect of particle size on the minimum energy required to ignite dust clouds of cornstarch in air by electrical sparks. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

Dusts of a given material produced by different manufacturing processes often have different shapes and surface characteristics that affect their flammability. This may result from differences in surface area, density, the amount of adsorbed gas, or the formation of protective surface layers. It is known, for example, that aluminum and magnesium powders produced by stamping, which yields flat, thin particles, have higher flammabilities than approximately spherical particles of the same mesh size produced by atomization or by milling.

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[5] I. Hartmann, J. Nagy, and H. Brown, *U. S. Bur. Mines Rept. Invest.* No. **3722**, 1943.

[6] I. Hartmann and J. Nagy, *U. S. Bur. Mines Rept. Invest.* No. **3751**, 1944.

[7] I. Hartmann, A. R. Cooper, and M. Jacobson, *U. S. Bur. Mines Rept. Invest.* No. **4725**, 1950.

3. Concentration of Dust Cloud

In a dust cloud, just as in a gas-air mixture, ignition of one part of the cloud will be propagated throughout the entire mixture and develop into an explosion only when the concentration of the dust in the air is between certain lower and upper limits. The minimum explosive concentration, or lower limit of explosibility, is that concentration at which there is just barely enough dust in the air to propagate flame throughout the cloud after ignition at a localized point. The upper explosive limit is theoretically that dust concentration at which the heat generated through complete combustion of a portion of the dust in the available oxygen is insufficient to raise the entire dust cloud to the ignition temperature.

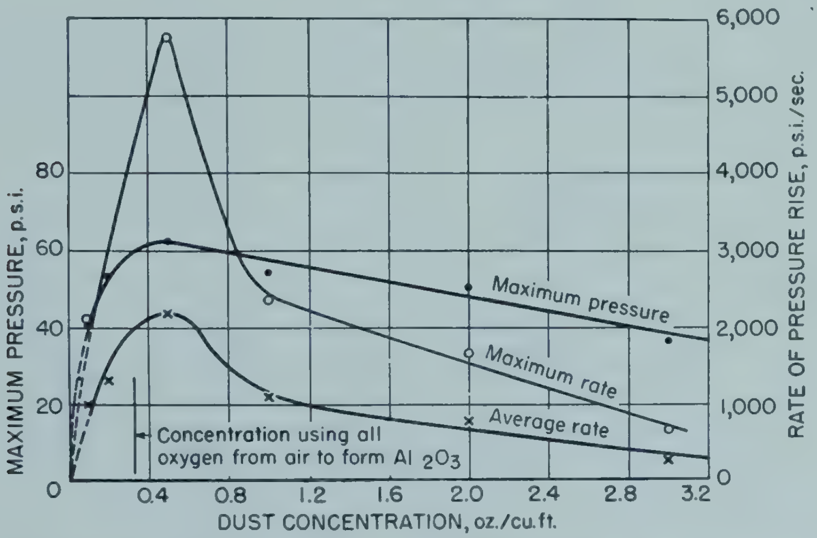

Figure 3. Maximum pressure and rates of pressure rise developed during explosions of aluminum powder at various concentrations.

Between these two limits there is an "optimum" concentration at which there is just enough dust in the cloud for complete combustion in the available oxygen. Neglecting dissociation, in a dust cloud of uniform concentration this optimum value should correspond to the stoichiometric mixture; actually it is always somewhat higher. The pressure developed and the speed of the explosion at the optimum dust concentration under most favorable conditions are greater than at lower or higher concentrations. The effect of concentration on the maximum pressures developed and on the rates of pressure rise in explosions of dust clouds of stamped aluminum powder can be seen in Figure 3. Similar data have been illustrated for other metal powders and metallic hydrides,[8] for bituminous coal,[3]

and for cornstarch;[7] the last paper also shows the effect of dust concentration o
ignition temperature of cornstarch dust clouds.

4. Composition of Atmosphere

The percentage of oxygen in the atmosphere containing a dust cloud affect its flammability. In an atmosphere of oxygen, dust clouds ignite at lower temperatures, the minimum igniting energy is smaller, and the minimum explosive concentration is lower than in air. This is illustrated for bituminous coal in Figure 1; additional studies show the effect of oxygen on pressures and rates in coal-dust explosions.[3] Decrease in oxygen content, on the other hand, reduces the ease of ignition and, in general, also the violence of explosion produced by a dust cloud. Figure 4 shows the variation of the minimum explosive concentration of aluminum

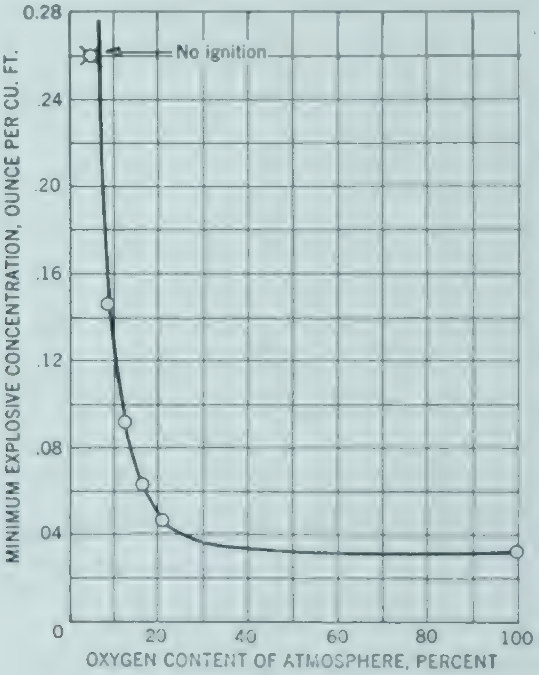

Figure 4. Effect of oxygen content of atmosphere on the minimum explosive concentration of atomized aluminum dust clouds. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

dust clouds with oxygen content of the atmosphere; this great effect is somewhat surprising because in lower-limit mixtures in air the available oxygen greatly exceeds the quantity necessary for complete combustion of the dust. For most dusts there exists a critical oxygen limit below which they will not ignite and propagate flame. Exceptions to this have been found in a number of metal powders, including zirconium, magnesium, titanium, thorium, uranium, and some magnesium-aluminum alloys, that ignite by electric sparks and propagate flame when dispersed in carbon dioxide. For reducing the flammability of most carbonaceous dusts, reduction of oxygen content by dilution of air with carbon dioxide proved to be slightly more effective than dilution to the same degree with nitrogen. The reason appears to be the higher specific heat per unit volume and therefore the greater cooling action of carbon dioxide than of nitrogen. For a few metal powders, however, dilution of the air with nitrogen was more effective than dilution with carbon dioxide, probably because the metal decomposed carbon dioxide more easily than it could combine with nitrogen. Argon proved to be about equally effective to nitrogen, and helium was in general more effective, possibly owing to its good heat conductivity.[8]

Normal variations in atmospheric humidity appear to have little direct effect on the flammability of dust clouds. However, high atmospheric humidity frequently results in formation of a conductive film of moisture on equipment, which promotes leakage of static electricity and reduces the hazard of ignition by static sparks. This may be quite important, especially with nonconducting dusts, during the processing of which considerable static charge might be developed at low humidities. The chief effect of moisture in dust is agglomeration of the particles and reduction of their dispersibility; in addition, some energy is required to heat and vaporize the moisture during ignition. Figure 5 shows the effect of moisture on the minimum explosive concentration of cornstarch dust clouds; other effects have been described by Hartmann and co-workers.[3,7]

5. Type of Ignition Source

Limited experiments have shown that when dust clouds are in contact with an ignition source for some time, so that the dust and air are preheated, they can be ignited at lower temperatures than is possible by instantaneous contact with the heat source; additional studies on this problem are in progress. It is also known that ignition can be effected at a lower temperature by large ignition sources, which come in contact with a greater portion of the dust cloud, than by localized ignition sources. Most carbonaceous and many other dusts are more difficult to ignite by electric sparks or arcs than by open flames and hot surfaces. There is evidence to indicate that the minimum explosive concentration of a dust cloud also is affected by the nature of the ignition source.[9]

6. Characteristics of Explosion Space

Although no controlled studies have been made concerning the exact effects of the size, shape, and other characteristics of containers or rooms in which dust explosions occur, it is known that they influence the distribution of the dust cloud, the propagation of flame through the cloud, and the pressures and rate of pressure rise during an explosion. Theoretically, higher maximum pressures should be developed by explosions of dust clouds of a given concentration in a large chamber than in a smaller space. However, uniformly distributed dust clouds in large enclosures are very rare in practical situations and quite difficult to produce experimentally. Studies of large-scale coal-dust explosions in mine entries have shown that as an explosion develops, partly as a result of precompression and preheating, the explosion pressure and flame speeds often increase with increasing distance from the point of initiation. It is also known that more violent explosions are developed in a turbulent dust cloud, as in a grinding mill, than in a still cloud of the same concentration.

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[8] I. Hartmann, J. Nagy, and M. Jacobson, *U. S. Bur. Mines Rept. Invest.* No. **4835,** 1951.

[9] L. J. Trostel and H. W. Frevert, *Chem. & Met. Eng.,* **30,** 141 (1924).

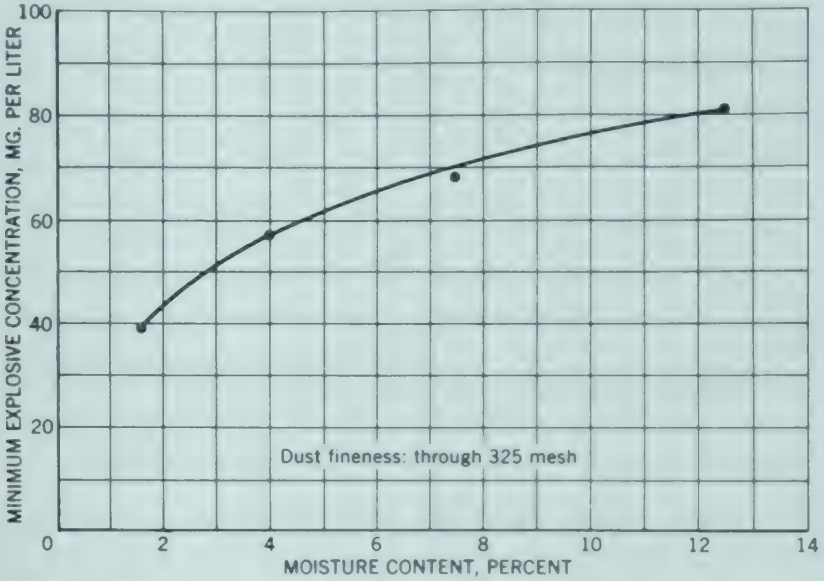

Figure 5. Effect of moisture on the minimum explosive concentration of cornstarch. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

II. Laboratory Data on Dust Explosibility

Studies of the explosibility of dusts have been made by numerous investigators here and abroad, and data have been obtained on ignition temperatures, minimum explosive concentrations, maximum pressures, and other related factors. In some instances the results published by different authors vary widely, owing in part to the great difficulty in producing and maintaining uniform dust clouds in test equipment, differences in experimental procedure, and variations in dust samples, especially in regard to purity and fineness. For these reasons it does not seem appropriate to report here more than a few detailed results. For further information the reader is referred to publications that he can consult.

In this country most of the experimental work on dust explosions has been conducted by the Bureau of Mines of the United States Department of the Interior at its Pittsburgh, Pennsylvania, laboratory; by the Bureau of Agricultural Chemistry and Engineering of the United States Department of Agriculture, Washington, D. C.; by the engineering department of the Factory Insurance Association, Hartford, Connecticut; by the laboratory of the Associated Factory Mutual

Insurance Companies, Boston, Massachusetts; and by the Underwriters' Laboratories, Inc., Chicago, Illinois. A good account of early experimental work, together with descriptions of many industrial dust explosions, is supplied by Price and Brown.[10] A brief discussion of the problem, with extracts of early experimental data from various sources, is given by Gibbs.[11] Many studies are described in reports and pamphlets issued by the organizations named above and in references cited in this chapter. A list of references to work of many investigators on ignition temperature measurements is included in a bibliography of a dissertation by Brown.[12]

A. DATA ON IGNITION TEMPERATURES

The ignition temperature of a solid can be defined in many ways, and various tests have been devised to determine the temperature according to the definition used. A common definition that may be accepted for the present purpose is "that temperature at which the substance takes fire spontaneously in air."

Edwards and Harrison[13] determined the ignition temperatures of quiescent layers of various dusts during prolonged heating in an electric furnace through which air was passed at a definite rate. The reported values are given in Table 1.

TABLE 1

Dust	Ignition temperature of dust layer (° C.)	Dust	Ignition temperature of dust layer (° C.)
Cellulose	354	Paper	327
Cocoa	237	Pyrethrum flowers	252
Corn-elevator	267	Tobacco	253
Cornstarch	324	Wheat-elevator	265
Ground cloves	253	Wheat smut	255
Ground oat hulls	272	Wood flour	277
Hard-wheat flour	327	Wood-pulp	272
Leather-fertilizer	324		

In studies on the explosibilities of dusts at the Bureau of Mines laboratory, the ignition temperatures of dust clouds in air were determined by projecting them downward through a cylindrical, electrically heated laboratory furnace, and the ignition temperatures of quiescent dust layers were measured by heating them in the furnace for several minutes. In the latter tests the thickness of the dust layers was generally about $^1/_8$ inch and the air flow ranged from $^3/_4$ to a few liters per minute. In very recent experiments on the effect of the thickness of dust layers it was found that, in the equipment used, the lowest ignition temperatures are reached with layers $^1/_2$ inch thick. In nearly all cases, 90 per cent or more of each powder was finer than 74 μ. Selected results are given for metal powders[5] in Table 2, for dusts in the plastics industry[6] in Table 3, and for agricultural and other dusts[14,15] in Table 4. Data for coal dust clouds in air and in oxygen and for layers of coal dusts of various volatile contents[3] are shown in Figure 1.

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[10] D. J. Price and H. H. Brown, *Dust Explosions, Theory and Nature of, Phenomena, Causes and Prevention.* Natl. Fire Protect. Assoc., Boston, 1922.

[11] W. E. Gibbs, *The Dust Hazard in Industry.* Ernest Benn, Ltd., London, 1925.

[12] C. R. Brown, *The Determination of the Ignition Temperatures of Solid Materials.* Catholic Univ. of America, Washington, 1934.

[13] P. W. Edwards and R. W. Harrison, *Ind. Eng. Chem., Anal. Ed.,* **2,** 344 (1930).

TABLE 2

Ignition Temperatures of Metal Powders

Powder	Ignition temperature (° C.) Dust cloud	Ignition temperature (° C.) Dust layer	Powder	Ignition temperature (° C.) Dust cloud	Ignition temperature (° C.) Dust layer
Aluminum, atomized	640	750	Manganese	450	450
Aluminum, stamped	550	470	Silicon	775	950
Antimony	415	330	Tin	630	430
Cadmium	570	250	Thorium	270	280
Chromium	900	—	Thorium hydride (ThH_2)[a]	260	20
Copper	700	—	Titanium	330	380
Dowmetal	430	480	Titanium hydride (TiH_2)	440	500
Iron, hydrogen reduced	315	290	Uranium[b]	20	100
Iron, carbon reduced	425	390	Uranium hydride (UH_3)[a,b]	20	20
Iron carbonyl	320	230	Vanadium	500	490
Lead, atomized	710	270	Zinc	600	460
Lead, stamped	580	300	Zirconium[b]	20	190
Magnesium, atomized	600	490	Zirconium hydride (ZrH_2)	350	270
Magnesium, milled	540	475	Ferrosilicon (88% Si)	860	—
Magnesium, stamped	520	480	Ferrotitanium, low-carbon	370	400
			Magnesium-aluminum (50-50)	535	460

[a] On exposure in air for several minutes at normal laboratory temperature, layers of ThH_2 and UH_3 ignited spontaneously.

[b] During dispersion through furnace at room temperature, dust clouds of U, UH_3, and Zr ignited.

TABLE 3

Ignition Temperatures of Dusts in Plastics Industry

Powder	Ignition temperature of dust cloud (° C.)	Powder	Ignition temperature of dust cloud (° C.)
Resins		Molding compositions	
Shellac, rosin, gum	390	Ethyl cellulose	320
Vinylbutyral	390	Rubber, synthetic	320
Cellulose acetate	370	Cellulose acetate butyrate	370
Pine-rosin base	440	Cellulose acetate	410
Polyethylene	410	Methyl methacrylate	440

[14] I. Hartmann, in L. S. Marks, *Mechanical Engineers' Handbook*, 5th ed., McGraw-Hill, 1951, pp. 795–800.

[15] I. Hartmann, *Ind. Eng. Chem.*, **40**, 752 (1948).

TABLE 3 (*continued*)

Powder	Ignition temperature of dust cloud (° C.)	Powder	Ignition temperature of dust cloud (° C.)
Lignin	450	Urea	450
Phenolic	460	Phenolic	490
Cellulose propionate	460	Polystyrene	560
Urea	470	Vinyl chloride–vinyl acetate	690
Polystyrene	490		
Allyl alcohol	500		
Coumarone-indene	520		
Polyvinyl acetate	520		
Chlorinated paraffin	840		
Resin ingredients		Fillers for molding compositions	
Sodium carboxymethyl cellulose	350	Ground alpha pulp	480
Hexamethylenetetramine	410	Ground cotton flock	470
Pentaerythritol	450	Ground wood flour	430
Resin stabilizer	510		
Rennet casein	520		
Phthalic anhydride	650		

TABLE 4

Ignition Temperatures of Agricultural and Other Dusts

Agricultural products	Ignition temperature of dust cloud (° C.)	Miscellaneous dusts	Ignition temperature of dust cloud (° C.)
Alfalfa	460	Aluminum stearate	400
Cellucotton	440	Bark dust, Douglas fir	540
Citrus peel, dehydrated	490	Coal, bituminous[a]	610
Clover seed	470	Cork	470
Cornstarch, ordinary	380	Dinitroorthocresol	440
Cornstarch, modified	460	Gilsonite	560
Corncob, ground, dried	400	Liver protein	520
Garlic, dehydrated	360	Napalm	450
Guar seed	500	Phenothiazine	540
Onion, dehydrated	410	*p*-Oxybenzaldehyde	380
Pea, dehydrated	560	Rubber, hard crude	350
Peanut cracklings	520	Soap	430
Rice	440	Sulfur	190
Soybean	520	Thyroid, desiccated	610
Sugar	350		
Tung kernels	440	Coal-tar pitch[b]	450–540[c]
Wheat, cracked	470	Water gas–tar pitch[b]	550
		Petroleum pitch[b]	430

[a] See Figure 1.

[b] Ignition temperatures for these samples were determined in atmosphere of oxygen; all other data in table determined in air.

[c] Value varies with volatile content.

B. MINIMUM EXPLOSIVE CONCENTRATIONS

There is probably greater variation in the values reported by different investigators of minimum explosive concentrations of dust clouds than for any other explosibility factor, because the uniformity of the dust cloud, which varies

TABLE 5

Minimum Explosive Concentrations of Metal Powders

Powder	Minimum concentration (mg./liter)	Powder	Minimum concentration (mg./liter)
Aluminum, atomized	40	Thorium	75
Aluminum, stamped	35	Thorium hydride	80
Antimony	420	Titanium	45
Dowmetal	20	Titanium hydride	70
Iron, carbonyl	105	Uranium	60
Iron, hydrogen reduced	120	Uranium hydride	60
Iron, carbon reduced	250	Vanadium	220
Magnesium, atomized	10	Zinc	480
Magnesium, milled	20	Zirconium	40
Magnesium, stamped	20	Zirconium hydride	85
Manganese	125	Ferrosilicon (88% Si)	425
Silicon	100	Ferrotitanium, low-carbon	140
Tin	190	Magnesium-aluminum (50-50)	50

TABLE 6

Minimum Explosive Concentrations of Dusts in Plastics Industry

Powder	Minimum concentration (mg./liter)	Powder	Minimum concentration (mg./liter)
Resins		Molding compositions	
Allyl alcohol	35	Cellulose acetate	35
Cellulose acetate	25	Cellulose acetate butyrate	25
Cellulose propionate	25	Ethyl cellulose	25
Coumarone-indene	15	Methyl methacrylate	20
Lignin	40	Phenolic	30
Phenolic	25	Polystyrene	15
Pine-rosin base	55	Rubber, synthetic	30
Polyethylene	20	Urea	75
Polystyrene	15		
Polyvinyl acetate	35		
Shellac, rosin, gum	15		
Urea	70		
Vinylbutyral	20		
Resin ingredients		Fillers for molding compositions	
Hexamethylenetetramine	15	Ground alpha pulp	60
Pentaerythritol	30	Ground cotton flock	50
Phthalic anhydride	15	Ground wood flour	40
Rennet casein	45		
Resin stabilizer	180		

according to the experimental procedure, is very important in the determination, and because different interpretations were placed on what constitutes a feeble explosion, such as is obtained at these low concentrations. For aluminum powder the published values[16] range from 7 to 432 mg. per liter and for sugar dust they range from 10.3 to 370 mg. per liter.[9] A dust concentration of 1 mg. per liter is approximately equal to 1 oz. per 1,000 cubic feet.

Tables 5, 6, and 7 list selected values of minimum explosive concentrations of metal, plastic, agricultural, and miscellaneous dusts and powders determined in the Bureau of Mines studies previously mentioned (see Figure 1 for data for coal in air and in oxygen). In general, these values are determined by dispersing varying quantities of dust samples in a cylindrical test vessel in which a high-voltage electric spark is formed across an approximately $^1/_4$-inch gap. The top of the vessel is closed by a filter-paper diaphragm, which ruptures upon ignition and explosion of a sufficiently dense dust cloud (see Figure 6). Recently the lower explosive limits of several dusts have been determined also in a continuous dust-air stream. For the most part, the results check the earlier data rather satisfactorily, but further refinements in the test procedure are being made.

TABLE 7

Minimum Explosive Concentrations of Agricultural and Other Dusts

Agricultural products	Minimum concentration (mg./liter)	Miscellaneous dusts	Minimum concentration (mg./liter)
Alfalfa	100	Aluminum stearate	15
Almond flour	150	Bark dust, Douglas fir	30
Cellucotton	50	Coal, bituminous[a]	50
Citrus peel, dehydrated	60	Coal-tar pitch	35
Clover seed	60	Cork	35
Cornstarch, ordinary	40	Dinitro-orthocresol	25
Cornstarch, modified	45	Gilsonite	20
Corncob, ground, dried	30	Liver protein	45
Garlic, dehydrated	100	Napalm	20
Guar seed	40	Phenothiazine	15
Onion, dehydrated	130	*p*-Oxybenzaldehyde	20
Pea, dehydrated	50	Rubber, hard crude	25
Peanut cracklings	85	Soap	45
Rice	45	Sulfur	35
Soybean	35	Thyroid, desiccated	60
Sugar	35		
Tung kernels	70		
Wheat, cracked	60		
Wheat flour	50		

[a] See Figure 1.

To date very little experimental work has been done on determination of the optimum concentrations and of the upper explosive limits of dust clouds. The latter values are rather indefinite because, as the concentration of most dust clouds is increased to high values, the combustion becomes more and more incomplete and there is no sharp limit beyond which explosions suddenly cease. The approximate upper explosive limit of coal-dust clouds in air has been found in recent tests to be in the range of 10 to 15 g. per liter. The values of optimum concentrations for many metal powders have been computed.[5]

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[16] R. B. Mason and C. S. Taylor, *Ind. Eng. Chem.*, **29**, 626 (1937).

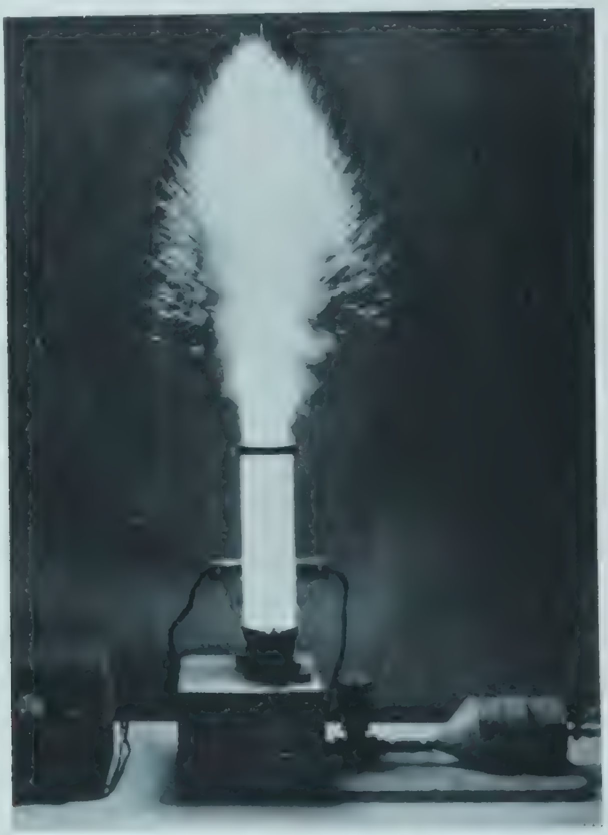

Figure 6. Explosion of 0.3 gram titanium powder in 1.3 liter cylindrical test vessel. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

C. MINIMUM ENERGY REQUIRED FOR IGNITION

The minimum energy required for ignition of dust clouds has been determined for many samples in experiments at the Bureau of Mines laboratory. In this work a condenser is charged to a definite potential, and formation of the dust cloud in the explosion vessel is synchronized with discharge of the condenser through the primary winding of a luminous-tube, step-up transformer. The potential induced in the secondary circuit of the transformer produces a spark between electrodes in the dust cloud, causing ignition (see Figure 6). Condensers of different capacities are used to determine the weakest spark needed to ignite the clouds. Some work has been done on the effects of voltage, series resistance, and other circuit parameters on ignition energy, and measurements also have been made with sparks produced by direct discharge of condensers.

TABLE 8

Minimum Energy Required for Ignition of Metal Powders by Electric Sparks

Powder	Minimum energy (millijoules) Dust cloud	Dust layer
Aluminum, atomized	15	2.5
Aluminum, stamped	10	1.5
Dowmetal	80	8
Iron, hydrogen reduced	80	160
Iron, carbon reduced	320	—
Iron carbonyl	20	80
Magnesium, atomized	120	40
Magnesium, milled	40	8
Magnesium, stamped	20	1
Manganese	80	3
Silicon	80	—
Tin	160	—
Thorium	5	0.004
Thorium hydride	3	.006
Titanium	10	.008
Titanium hydride	60	1.6
Uranium	45	.004
Uranium hydride	5	.032
Vanadium	60	—
Zinc	650	—
Zirconium	5	.001
Zirconium hydride	60	.064
Magnesium-aluminum (50-50)	80	20

TABLE 9

Minimum Energy Required for Ignition of Dusts in Plastics Industry by Electric Sparks

Powder	Minimum energy for ignition of dust cloud (millijoules)
Resins	
Cellulose acetate	10
Cellulose propionate	45
Coumarone-indene	10
Lignin	20
Phenolic	10
Polyethylene	30
Polystyrene	15
Polyvinyl acetate	120
Shellac, rosin, gum	10
Urea	80
Vinyl butyral	10
Resin ingredients	
Hexamethylenetetramine	10
Pentaerythritol	10
Phthalic anhydride	15
Rennet casein	60
Resin stabilizer	40
Molding compositions	
Cellulose acetate	40
Cellulose acetate butyrate	30
Ethyl cellulose	10
Methyl methacrylate	15
Phenolic	10
Polystyrene	40
Rubber, synthetic	30
Urea	80
Fillers for molding compositions	
Ground alpha pulp	80
Ground cotton flock	25
Ground wood flour	20

The minimum energy needed for ignition of undispersed dust layers has been determined by direct discharge of condensers of relatively low potentials. A thin layer of dust is placed on a flat metal plate, connected to ground, and a needlepoint electrode connected to the positive terminal of the condenser is lowered above the dust until a spark discharge occurs.

Data on minimum energies required for ignition of dust clouds and undispersed layers of metal powders are given in Table 8; for ignition of dust clouds of synthetic resins, molding compounds, resin ingredients, and fillers in Table 9; and for ignition of clouds of agricultural and other dusts in Table 10 (see also Figures 1 and 2). In the metal-powder group layers of some metals, notably zirconium, titanium, thorium, and uranium, ignited by sparks having energies of one to a few microjoules. Dust clouds of several metals and other materials ignited by sparks with energies of 10 or less millijoules (1 joule = 0.00095 B.t.u.).

TABLE 10

Minimum Energy Required for Ignition of Agricultural and Other Dusts by Electric Sparks

Agricultural products	Minimum energy for ignition of dust cloud (millijoules)	Miscellaneous dusts	Minimum energy for ignition of dust cloud (millijoules)
Alfalfa	320	Aluminum stearate	15
Cellucotton	60	Bark dust, Douglas fir	40
Citrus peel, dehydrated	45	Coal, bituminous	50
Clover seed	80	Coal-tar pitch	20
Cornstarch, ordinary	30	Cork	45
Cornstarch, modified	40	Gilsonite	25
Corncob, ground, dried	60	Liver protein	45
Guar seed	60	Napalm	40
Peanut cracklings	370	*p*-Oxybenzaldehyde	15
Rice	40	Rubber, hard crude	50
Soybean	50	Soap	60
Sugar	30	Sulfur	15
Tung kernels	240	Thyroid, desiccated	60
Wheat, cracked	160		

D. MAXIMUM PRESSURE AND RATES OF PRESSURE RISE IN DUST EXPLOSIONS

The maximum pressure and rate of pressure rise indicate the seriousness of a dust explosion and serve as a guide to the amount and type of venting that must be provided in a building or machine to release explosion pressures before structural damage occurs. Data on pressures and rates developed by explosions of 133 agricultural and other dusts were obtained in the laboratory of the United States Department of Agriculture and are published in a paper by Edwards and Leinbach.[17] At the Bureau of Mines laboratory studies have been made of the effects of dust concentration, fineness, moisture, uniformity of dust cloud, initial pressure, and other parameters on explosion pressures and rates; recent work has shown that the manner of forming the dust clouds in the test bomb is a most important factor. With the improved technique, much higher pressures and rates have been produced than formerly. These data help to explain the great destruction that had been observed in a number of industrial explosions.

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[17] P. W. Edwards and R. L. Leinbach, *U. S. Dept. Agr. Tech. Bull.* No. **490**, 1935.

Table 11 lists pressure data from the paper by Edwards and Leinbach for selected dusts, and Tables 12, 13, and 14 are values for a number of metal powders, plastics, and agricultural and other dusts from Bureau of Mines studies.[3,5–8,14] The pressures in these tables were determined at concentrations of 500 mg. per liter and are not necessarily the highest developed in the experiments, but not enough comparative data are available for many dusts at different concentrations and by the latest dispersion techniques. For rates of pressure rise and for other

TABLE 11

Dust Explosion Pressures from Department of Agriculture Study[17]

Dust	Explosion pressure (p.s.i.)	Dust	Explosion pressure (p.s.i.)
Cork and other barks	40	Carbon, coal, etc.	48
Fertilizers	51	Cocoa	23
Grain	46	Drugs	43
Milk powders	42	Flours	42
Starches	47	Meals	41
Sugars	45	Resins, soaps, waxes	42
Sulfur	32	Spices	43
Woods	44		

TABLE 12

Pressures Developed by Explosions of Metal Powders
(Dust concentration: 500 mg./liter)

Powder	Explosion pressure (p.s.i.)	Powder	Explosion pressure (p.s.i.)
Aluminum, atomized	90	Titanium	80
Aluminum, stamped	100	Titanium hydride	95
Antimony	6[a]	Vanadium	35[a]
Dowmetal	85	Zinc	50
Iron, hydrogen reduced	45	Zirconium	65
Iron, carbon reduced	25[a]	Zirconium hydride	60
Iron carbonyl	50	Ferrotitanium, low-carbon	55
Magnesium, atomized	80	Ferrosilicon (88% Si)	90
Magnesium, milled	95	Magnesium-aluminum (50-50)	90
Magnesium, stamped	80		
Manganese	50		
Silicon	105		
Tin	35		

[a] These pressures were determined by a testing technique used several years ago; all other values were measured by an improved method.

TABLE 15

Relative Flammabilities of Dusts

Powder		Relative flammability (%)	
		In furnace test	In spark test
Metals			
Aluminum, atomized		10	78
Aluminum, stamped		60	80
Antimony		65	18
Cadmium		18	0
Chromium		0	0
Copper		3	0
Dowmetal		90	90
Iron, hydrogen reduced		90+	55
Iron, carbon reduced		90+	43
Iron carbonyl		85	60
Magnesium, stamped		90+	90+
Magnesium, milled		90+	90
Lead, stamped		20	0
Manganese		40	25
Silicon		0	33
Tin		10	30
Titanium		90	85
Titanium hydride		80	70
Zinc		35	45
Zirconium		90+	90+
Zirconium hydride		85	80
Miscellaneous dusts			
Corn starch		90+	90
Peat moss		90+	80
	Volatile ratio (%)		
Anthracite	5.0	0	0
Low-volatile coa	18.5	60	0
Medium-volatile coal	27.2	85	40
High-volatile coal (Pittsburgh seam)	40.7	90	65
Subbituminous coal	42.8	90	75
Lignite	47.3	90	75
Coal-tar pitch, hard	45.1	—	68
Coal-tar pitch, soft	60.1		80
Water gas-tar pitch	49.0	—	70
Petroleum pitch	66.3	—	85
Resins			
Cellulose acetate		90+	83
Cellulose acetate butyrate		90+	83
Chlorinated paraffin		0	0
Coumarone-indene		90+	90+
Lignin		90+	78
Phenolic		90+	90
Polystyrene		90+	90
Polyvinyl acetate		90+	73
Shellac, rosin, gum		90+	90+
Urea		85	60
Vinylbutyral		90+	80
Molding compositions			
Cellulose acetate		90+	80
Cellulose acetate butyrate		90+	90
Ethyl cellulose		90+	90
Methyl methacrylate		90+	78
Phenolic		90+	80
Polystyrene		90+	90+
Rubber, synthetic		90+	80
Urea		90+	68
Vinyl chloride–vinyl acetate		5	0
Resin ingredients			
Hexamethylenetetramine		90+	90+
Pentaerythritol		90+	90
Phthalic anhydride		90+	90
Rennet casein		90	35
Fillers for molding compositions			
Ground alpha pulp		90+	85
Ground cotton flock		90+	73
Ground wood flour		90+	80

considerably greater than for the same materials in bulk. In general the dusts ignite at lower temperatures, they burn more rapidly, and the fires are more difficult to extinguish than for larger pieces.

The ignition temperatures of undispersed layers of dusts (see Tables 1 and 2 and Figure 1) are one index of the potential fire hazard. Another index is the minimum spark energy required for ignition of dust layers (see Table 8). This shows that fires in dusts might be started by weak electric sparks or arcs, including static sparks, as well as by heating from hot surfaces, by glowing particles, frictional sparks, open flames, or other causes.

Under ordinary circumstances of handling and storage, most dusts oxidize so slowly that the heat of oxidation does not produce an appreciable rise in the temperature of the dust. However, there are some dusts, including certain agricultural products, activated carbonaceous materials, and some metal powders, that oxidize rapidly and heat to the point of ignition under suitable conditions. Heating is influenced by the exposed surface, the density and depth of the stored dust, the temperature of the surroundings, air flow, heat losses from dust, time between preparation of dust and its storage, moisture content, etc. Some metal powders react with moisture, especially at elevated temperatures, to form hydrogen, which reduces the protective oxide film on the metal particles, facilitating their ignition.

Recent experiments in England indicate that many dusts are capable of prolonged, often undetected, smoldering, even in thin dust deposits. The smoldering can be initiated by very small sources, such as a glowing cigarette end, and under right conditions it can result in a delayed, severe fire. The opinion is expressed that many fires, formerly thought to have originated by spontaneous heating, might have started in this manner.

A. PREVENTION OF DUST EXPLOSIONS AND FIRES

The problem of preventing dust explosions is of such great importance in industrial plants that considerable effort has been devoted to its solution. To this end the Dust Explosion Hazards Committee of the National Fire Protection Association through its subcommittees has formulated a series of safety codes[17a] that embody detailed recommendations for a number of industries; much of the technical information in these was derived from the experiments to which reference has been made here. The reader is referred to these codes as a helpful guide in the design and construction of buildings and equipment and in regard to safe operating procedures. The subject is also being considered by the Research Committee of the President's Conference on Occupational Safety, by the National Safety Council, and by other groups concerned with reduction of accidents. So far NFPA dust-explosion codes have been prepared for the following operations and situations:

1. Aluminum-bronze powder manufacture (No. 651)
2. Magnesium powder or dust (No. 652)

[17a] *The National Fire Codes,* Vol. II, *Combustible Solids, Dusts, Chemicals, and Explosives.* Natl. Fire Protect. Assoc., Boston, 1956.

3. Coal pneumatic cleaning plants (No. 653)
4. Plastics industry (No. 654)
5. Flour and feed mills (No. 61C)
6. Pulverized-fuel systems (No. 60)
7. Confectionery plants (No. 657)
8. Spice-grinding plants (No. 656)
9. Starch factories (No. 61A)
10. Sugar- and cocoa-pulverizing systems (No. 62)
11. Sulfur dust (No. 655)
12. Terminal grain elevators (No. 61B)
13. Suggested good practices for the application of suction and venting for the control of dust in grain elevators and storage units (No. 661)
14. Country grain elevators (No. 64)
15. Wood-flour manufacturing establishments (No. 662)
16. Woodworking plants (No. 663)
17. Aluminum processing and finishing (No. 65)

Other pertinent NFPA standards and pamphlets are:

1. Standard for fire and explosion prevention by inerting (No. 69)
2. Pamphlets on combustible metals
3. Guide for explosion venting (No. 68)
4. Pamphlet on static electricity
5. National electrical code

Important recommendations in these codes include:

1. All possible ignition sources should be eliminated from equipment containing flammable dust and from areas surrounding such equipment. This means prohibiting open flames or lights and smoking; avoiding the use of electric or gas cutting or welding equipment for repair work, unless dust-producing machinery in that part of the plant is shut down and the vicinity is entirely dust-free; grounding all machinery capable of producing static electrical sparks; providing conduits for electric wiring and locating switches and motors outside, or using dustproof types; adhering strictly, in installing wiring and electrical equipment, to the rules of the National Electrical Code pertaining to hazardous locations; using magnetic separators to prevent entrance of hazardous materials to dust-grinding mills; using nonferrous blades in fans through which dust passes; and avoiding the use of high-speed shafting and belts wherever possible.

2. Buildings should be constructed to avoid the collection of dust on beams, ledges, and other surfaces, particularly overhead. Good housekeeping is a prime essential in preventing dust accumulation and dissemination. In removal of dust from exposed surfaces, vacuum cleaning is preferable, although soft push brooms may be used without serious hazard; for highly flammable dusts industrial vacuum cleaners of approved design are recommended. Use of compressed air for dust removal is highly dangerous. Buildings in which flammable dusts are produced or stored should be detached units of incombustible construction, including inside partitions; and hazardous areas within buildings should be separated by substantial fire walls.

3. Equipment wherein dust clouds may be produced, such as grinders, conveyors, elevators, or collectors, should be as dust-tight as possible; it should have the smallest practical interior volume; and it should be constructed strong enough to withstand explosion pressures from dust.

4. Properly designed and proportioned and properly distributed vents, in the form of unrestricted openings if possible; hinged windows, panels, or light wall construction in rooms; and the use of release diaphragms or other vent closures in equipment will release explosion pressures without damage.

In recent years much work on venting has been performed by the Bureau of Mines[18–20] in explosion galleries of several sizes. The pressure-release requirements of various dusts have been determined with unrestricted vents (Figure 8), and the relative effectiveness of numerous diaphragms was studied.[19] Many of the data on venting through ducts of various shapes and sizes, effects of bends in ducts, secondary vents in ducts, flame speeds in ducts, quenching of explosions in ducts, and quenching during the incipient stages of ignitions have not been published yet, and the research is in fact still being continued.

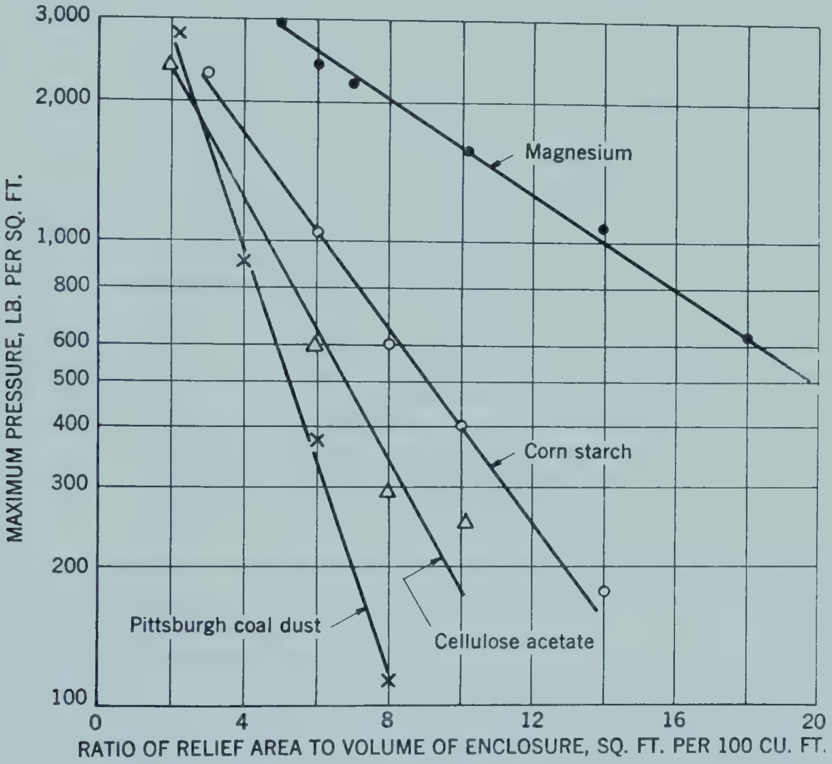

Figure 8. Effect of unrestricted relief vents on pressures developed by dust explosions in 1 cubic foot test gallery. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

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[18] I. Hartmann and J. Nagy, *U. S. Bur. Mines Rept. Invest.* No. **3924,** 1946.

[19] I. Hartmann, Pressure release for dust explosions, *Natl. Fire Protect. Assoc. Quart.*, **40,** 47–53 (July, 1946).

[20] J. Nagy, J. E. Zeilinger, and I. Hartmann, *U. S. Bur. Mines Rept. Invest.* No. **4636,** 1950. See also I. Hartmann, *Chem. Eng. Progr.*, **53,** 107M (1957); I. Hartmann and J. Nagy, *Ind. Eng. Chem.*, **49,** 1734 (1957).

Under special conditions the products of combustion during an explosion cannot be released immediately to the outside atmosphere but may have to be diverted into adjoining spaces of larger but finite dimensions. In such circumstances the pressure in the explosion space does not necessarily decrease with increase in vent area (see Figure 9) because part of the dust mixture is ejected into and explodes in the larger chamber.

The proper areas of vents and the suitability of a vent closure depend on several factors, which include: (*a*) strength of structure or enclosure; (*b*) the maximum explosion pressure and the average rate of pressure rise of the explosive dust; (*c*) the position of the vents with respect to the origin of the explosion; (*d*) bursting strength of the vent closure, or the minimum pressure required to open the vent closure if movable as a whole; (*e*) the inertia of the vent closure. Recommended (unrestricted) venting areas range from 1 square foot for each 10 to 30 cubic feet of enclosure for small equipment and light construction, to 1 square foot per 80 cubic feet for large rooms and buildings with heavy, reinforced concrete construction. Additional recommendations on this subject are given in the NFPA Guide for Explosion Venting.

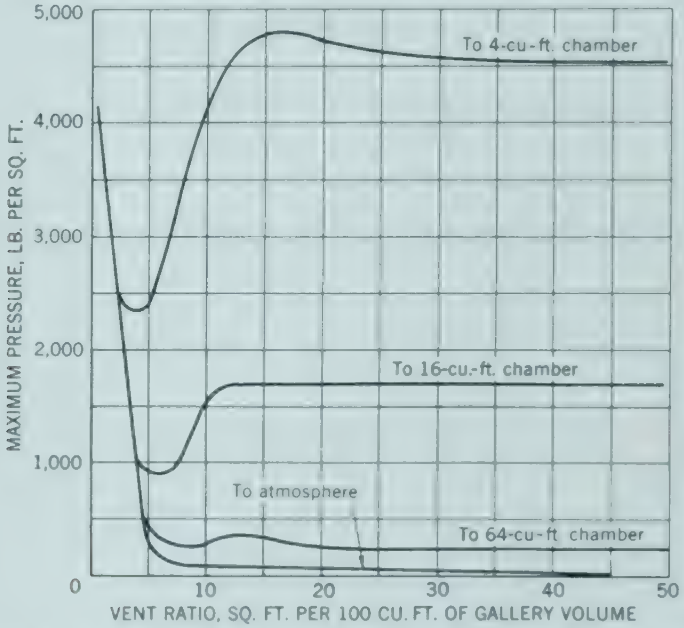

Figure 9. Venting coal dust explosions from 1 cubic foot gallery to atmosphere and to cubical chambers of various sizes. (Courtesy Bureau of Mines, U. S. Department of the Interior.)

5. Dust collectors should preferably be located outside of buildings or in detached rooms provided with adequate explosion vents; this applies particularly to dry collectors. For certain dusts, wet collectors, preferably of liquid precipitation type, are recommended; these should have positive ventilation of the sump. Individual dust-collection units, installed close to the dust source, should be used. Ducts leading to and from collectors should be as short and straight as possible

Blowers for drawing dust-laden air into collectors should be on the clean-air sides of collectors.

6. Grinding, conveying, and other equipment can frequently be protected by introducing a continuous flow of inert gas into the equipment, thereby reducing the normal oxygen content to a point at which the dust will not explode.[21] The inert gas for this purpose can be obtained by purifying furnace or boiler flue gases; by hydrocarbon combustion, ammonia combustion, or air fractionation; dilution of air with carbon dioxide or with nitrogen from high-pressure cylinders; or by use of argon or helium. Various methods of producing and using inert gases are described in the NFPA Standard for Fire and Explosion Prevention by Inerting.

TABLE 16

Maximum Permissible Oxygen Content to Prevent Ignition of Combustible Metal Powders

	Limiting percentage of oxygen, spark ignition[a]			
Type of dust	Air-CO_2 mixture	Air-N_2 mixture	Air-He mixture	Air-A mixture
Aluminum, atomized	7	9	10	—
Antimony	16	—	—	—
Iron, hydrogen reduced	13	—	—	—
Iron carbonyl	10	—	—	—
Magnesium, atomized	<3	2	3	—
Magnesium, milled and stamped	[b]	—	—	—
Manganese	15	—	—	—
Silicon	13	—	—	—
Tin	16	—	—	—
Vanadium	13	—	—	—
Zinc	10	10	—	—
Dowmetal	[b]	3	3	—
Ferrotitanium, low carbon	13	—	—	—
Ferrosilicon (88% Si)	19	—	—	—
Magnesium-aluminum (50-50)	[b]	6	6	
Thorium	[b]	2.5	5	2
Thorium hydride (ThH_2)	6	5	5	4
Titanium	[b]	6	7	4
Titanium hydride (TiH_2)	13.5	10	8.5	8
Uranium	[b]	1.5	2.5	2
Uranium hydride (UH_3)	0.5	2.5	4	2
Zirconium	[b]	4	5	4
Zirconium hydride (ZrH_2)	11	8	8.5	6

[a] In the furnace test, dust clouds of Zr, Th, U, and UH_3 also ignited in CO_2. During heating for several minutes undispersed layers of samples of the following metal powders ignited (glowed) in CO_2: stamped Al, Mg, Zn, Mg-Al, Dowmetal, Ti, TiH_2, Zr, ZrH_2, Th, ThH_2, U, and UH_3. Visible burning of dust layers was also observed in N_2 with powders of Mg, Sn, Mg-Al, Dowmetal, Ti, TiH_2, Zr, Th, ThH_2, U, and UH_3.

[b] Dust clouds of these powders ignited by electric spark in an atmosphere of commercial CO_2.

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[21] H. R. Brown, *U. S. Dept. Agr. Tech. Bull.* No. **74**, 1928.

The maximum allowable percentages of oxygen in inert gas used for preventing the explosion of dusts have been determined at the Bureau of Mines laboratory for numerous metal powders, dusts in the plastics industry, and coals and other products. The experiments were performed in part in the presence of high-voltage electrical induction sparks and in part in a heated laboratory furnace, mostly at

TABLE 17

Maximum Permissible Oxygen Content to Prevent Ignition of Combustible Plastics Industry Dusts

Type of dust	Limiting percentage of oxygen	
	Furnace test, 850° C. ($Air-CO_2$ mixture)	Spark ignition ($Air-CO_2$ mixture)
Resins		
Allyl alcohol	7	—
Cellulose acetates[a]	5	13
Coumarone-Indene	11	14.5
Lignin	7	17
Phenolic	9	14.5
Pine-rosin base	5	—
Polyethylene	8	13
Polystyrene	7	14
Polyvinyl acetate	11	17
Shellac, rosin, gum	9	14.5
Urea	11	17
Vinylbutyral	5	14.5
Molding compositions		
Cellulose acetate compounds	7	11.5
Methyl methacrylate	7	14.5
Phenolic	7	14.5
Polystyrene	9	14
Rubber, synthetic	11	15
Urea	9	17
Vinyl	15	—
Resin ingredients		
Hexamethylenetetramine	11	14.5
Pentaerythritol	7	14.5
Phthalic anhydride	11	14.5
Rennet casein	7	17
Resin stabilizer	13	15
Sodium carboxymethylcellulose	6.5	—
Fillers for molding compositions:		
Alpha pulp, ground	7	17
Cotton flock, ground	7	17
Wood flour	7	17

[a] To prevent ignitions of dust clouds of cellulose acetate by dilution of the atmosphere with N_2, the limiting oxygen percentages were determined to be 3% in the furnace test and 9.5% in the spark test.

850° C. temperature; the latter proved to be the more severe igniting source. Data have been obtained for most dusts by diluting air with carbon dioxide, but for a number of metal powders the oxygen limits were determined also in air-nitrogen, air-helium, and air-argon mixtures. The information is given in Tables 16, 17, and 18.

TABLE 18

Permissible Oxygen Content to Prevent Ignition of Miscellaneous Combustible Dusts

Type of dust		Limiting percentage of oxygen: Furnace test, 850° C. (Air-CO_2 mixture)	Limiting percentage of oxygen: Spark ignition (Air-CO_2 mixture)
Bark dust, Douglas fir		—	16
Rubber, hard crude		—	15
Phenothiazine		—	16
Coal dust	(Volatile ratio, per cent)		
Semianthracite	9.3	11.5	—
Low-volatile	18.5	10.5	—
Medium-volatile	27.2	10.5	18.5
High-volatile A	40.7	10.5[a]	16
High-volatile C	51.7	10.5	15
Lignite	47.3	7.5	15
Coal-tar pitch		—	15–17.5[b]
Water gas–tar pitch		—	16.5
Petroleum pitch		—	11

[a] The following data were obtained with a sample of pulverized (all particles smaller than 74 μ) high-volatile A coal dust from the Pittsburgh seam, on the effect of temperature on the limiting percentage of oxygen:

Furnace temperature (° C.)	Limiting percentage of oxygen
500	100
620	21
650	19
700	15
750	11
800	10.5
850	10.5

[b] Limit varies with volatile content.

In addition to the use of inert gas, it is sometimes feasible to prevent the formation of explosive dust-air mixtures or to reduce the explosion hazard in industrial plants by adding inert dusts to the combustible dust (Figure 7), a procedure similar to that employed in coal mines for preventing propagation of coal-dust explosions.

Sometimes it is also possible to make use of high atmospheric humidity in the equipment or room containing flammable dust. It may reduce somewhat the ease of dispersion and might make ignition slightly more difficult. As a rule, however, reliance on this practice or on the effect of a small amount of moisture in dust is not recommended, because the dust still can be thrown into suspension and ignited by a strong source of ignition. The usefulness of high humidity lies chiefly in preventing or reducing the accumulation of static electricity on the dust.

7. With respect to fire prevention and fire extinguishing in flammable dusts, in addition to the usual recommendations for fire prevention, the following points should be noted: (*a*) Attention should be directed to the hazard of possible spontaneous heating in many powdered products, particularly after grinding. (*b*) Efforts should be made to detect and eliminate smoldering particles in dust deposits, especially before periods of plant shutdown. (*c*) First-aid protective equipment should be installed that is suitable for fires in combustible dusts, such as small hose, water pails, soda-acid extinguishers, and hand-operated water pump tanks. A small hose equipped with a spray-type nozzle is satisfactory for most dusts. The fine spray wets the dust and is not as apt to produce a dust cloud as is a solid stream. (*d*) Large hose streams of fire-department sizes should be used only with great caution where combustible dusts are involved, because dust might be thrown into suspension by their use, with a consequent explosion. Plant employees and the fire department should be advised of this danger in advance of trouble. (*e*) Spray or fog nozzles can be used without danger of disturbing dust deposits, and nozzles of this type should be available with all hose used for fire protection where combustible dust is present. (*f*) Small fires in magnesium, aluminum or other metal powders are best extinguished by sand, talc, soapstone, or other dry inert materials applied gently to surround and smother the fire, or in some circumstances by the use of such materials as hard pitch, which completely seal the powder from the air.[22]

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[22] H. R. Brown, I. Hartmann, and J. Nagy, *U. S. Bur. Mines Rept. Invest.* No. 3672, 1942

CHAPTER XVII

Physiological Effects of Abnormal Atmospheric Pressure*

HEINZ SPECHT

I. Introduction—Historical Background

The effects of the pressure exerted by the atmosphere upon the body, especially those that follow changes in this pressure, for convenience are considered in two classes, linked by the common physical attributes of gases. They comprise those found *(1)* in the range from normal barometric pressure to positive pressures met in diving and caisson work and *(2)* in the range from normal to the reduced pressures incident to ascent into the atmosphere, respectively. As will be seen subsequently, certain details of the response to these two alterations in atmospheric pressures are different and necessitate separate discussion. In general, however, there is a continuity of response that has permitted a mutual acceleration of understanding of problems arising in these fields.

Historically, the elucidation of essential factors under both conditions rests on observation and practices of long standing, on the one hand in the diving industry, and on the other hand in agriculture and mining in mountainous areas, which have been implemented from ancient times by special knowledge, uncritical though it may seem in the light of more recent observation and experiment.

It is probable that pearl and sponge diving offered the earliest and most frequent industrial encountering of effects of compressed air. It seems likely that no realization of the physiological aspects existed until the time of Aristotle,[1] and then only to the extent that he wrote of the practicality of inverting a kettle of air over the head as an aid in prolonging diving operations. Roger Bacon is reported to have invented a diving bell about 1250 A.D.[1,2] It was not until the seventeenth century that advances in diving technique were made rapidly. The advances made in that century served to recover the riches sunk with the Spanish Armada.[3] It was another century before pumps were used to supply air to divers, and it was with this means of prolonging diving time that intimations of physiological factors began to appear in the scientific writings. It was no longer a matter of "fresh air" but the realization that compression and more especially decompression were hazardous and required deliberate and slow schedules for the attainment of gaseous equilibrium between the body and its environment. A logical basis for decompression was not discovered until Paul Bert[1,2,4] did his fundamental work on the effects of atmospheric pressure on the body.

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[1] R. Heller, W. Mager, and H. Schrötter, *Luftdruckerkrankungen mit besonderen Rücksichtigung der sogennanten Caissonkrankheit,* Vol. I. Hölder, Vienna, 1900.

[2] Heller *et al., op. cit.,* Vol. II.

The effects of rarefied atmospheres were known in ancient times, but the only significant deductions were concerned with their geographic distribution. Thus, the inhabitants of Alpine, Himalayan, and Andean regions were known to be industrious and healthy people casually undifferentiable from the lowlanders, yet the latter in travels through these regions collapsed or at least were ill and incapable of exertion. However Acosta, in 1590,[1,2] wrote that in trans-Andean trips even the natives were affected by extreme altitude, and he rightly concluded that the "fine and thin air" was unsuited to the requirements of respiration.

It was not until abrupt ascent into the atmosphere became feasible that the pioneer balloonists found—by bitter experience—the necessity for detailed knowledge of the effects of lowered atmospheric pressure on the body. It was again the researches of Paul Bert[4] from 1871 to 1883, spurred on by the tragic outcome of ascents of Sivel, Croce-Spinelli, and Tissandier (1875), that started the analysis of these effects and laid a rational groundwork for the entire field.

In essence, the problems in physiology presented by abnormal atmospheric pressure deal with the vagaries of the physical solution of gases in the body fluids, the pressure-labile chemical changes of oxygen and carbon dioxide in the body, and the concomitant effects of these factors on the complex systems of adjustment that the mammalian organism, in particular, has evolved.

Because of certain differences, in various factors, that exist between the two types of abnormal pressure, increased and reduced pressure will each be considered separately and then followed by a discussion of the common properties. In order to understand the intimate difficulties encountered by the body in each of the two ranges of pressure it is necessary to recapitulate the properties of gases of the atmosphere, first, with respect to each other and their geographical distribution and, second, with respect to their individual characters. (For a detailed treatment of the subject see the excellent work of Humphreys.[5])

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[3] Meyer, *Conversations Lexicon*. 5th ed., Bibliographisches Institute, Leipzig and Vienna, 1893.

[4] P. Bert, *La pression barométrique*. Available in English as *Barometric Pressure*. Trans. by M. A. and F. A. Hitchcock, College Book Co., Columbus, Ohio, 1943.

[5] W. J. Humphreys, *Physics of the Air*. 3rd ed., McGraw-Hill, New York, 1940.

II. Properties of the Atmosphere

A. COMPOSITION

The composition of the atmosphere near the earth's surface is given in Chapter VI (page 143), and therefore the components will not be tabulated here.

With the exception of carbon dioxide and ozone, the gases normally present in the air are distributed in relatively unvarying percentages from the level of depressions (—1292 feet in the Dead Sea Basin) to an altitude of about 65,000 feet. Above this altitude there is no thermal mixing of the atmosphere and there is evidence that a progressive decrease in the concentration of the heavier gases occurs, as a result of gravitational separation. This level is above the altitude at which, on theoretical grounds, the boiling point of water in the body would be attained and far above the level at which pure oxygen will no longer suffice for supplying the metabolic needs. The composition of the atmosphere at these altitudes is mainly of engineering interest in the construction of stratosphere craft depending on ambient gases for pressurization of cabins.

The presence of such a variable constituent as ozone is accounted for by different theories. Besides local concentrations due to electrical discharges through the atmosphere there is a diffusion of ozone downward from extreme altitudes at which oxygen is thought to be converted to ozone by the absorption of energy from the sun.[6] Its instability prevents any accumulation to deleterious concentrations, as far as is known, in the vital altitude range given above.

Carbon dioxide is present in appreciable concentration only near the surface of the earth and may accumulate to a variable extent only in confined or circumscribed areas in which combustion of carbon or other release of carbon dioxide is taking place. In nature it may become a limiting factor for life, for example, in certain grottoes where various processes free carbon dioxide from the rock to accumulate in the air in high concentration.[7] Carbon dioxide is also encountered in dangerous concentration in caisson work, in mines, and in tunnels.[4]

In general, water vapor in the external air does not limit the use of the atmosphere for respiratory purposes, but as will be seen later, at high altitudes water vapor can physically displace other gases from the lungs. As far as can be ascertained, its concentration in air of caissons and tunnel heads produces no serious deleterious effects. In the external atmosphere it attains a very low value at the lower level of the isothermal layer[6] (stratosphere).

The only instances of significant concentrations of abnormal constituents and excessive concentrations of normal constituents are in situations similar to the above, that is, in confined or restricted areas. Conditions often are aggravated by the fact that these abnormal constituents form layers whose concentrations are inimical to life. In any case, the factor of natural positive atmospheric pressure is of importance only because chemical reactions in metabolic systems depend in many cases on the partial pressure of the gaseous reactants, and thus identical concentration ratios may have widely different effects as the barometric pressure varies. The discussion of toxic effects of abnormal air constituents is not germane to this chapter.

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[6] S. Ruff and H. Strughold, *Grundrisse der Flugfahrtmedizin*. Barth, Leipzig, 1939.

[7] E. L. Quinn and C. L. Jones, *Carbon Dioxide*. Reinhold, New York, 1936.

B. PHYSICAL ATTRIBUTES OF ATMOSPHERIC GASES AND FUNDAMENTAL PHYSIOLOGICAL ASPECTS

A visualization of the properties of gases is based on the kinetic theory of matter. Briefly stated, this assumes that gas molecules are in constant motion with an average velocity that is dependent on the temperature. They travel in straight lines until impact with another molecule of any kind changes their direction of motion and velocity. Pressure is exerted by a gas in the sense that force is applied by the impinging of its molecules upon all surfaces. This pressure is measured as force per unit area. The intermolecular distances in a gas are normally greater than those in a liquid or a solid, the latter differing mainly in the assumption that the molecules of a liquid slide over and about each other while those in a solid are fixed in relation to each other. More specifically, the following attributes of gases may be described here:

1. *Mass and Weight*

Mass may be defined as the amount of matter in a substance. It has the properties of inertia and of attraction for other masses. Mass is measured by the acceleration produced when a standard force acts on the inertia of the substance. It is specific for each kind of molecule. The mass of a substance multiplied by the acceleration due to the earth's attraction (gravity) is called its weight.

2. *Density*

This property of gases, common to all matter, is defined by the relation of mass or weight to unit volume. Thus at 1 atm. pressure and at 0° C.[5] 1.429 g. per liter is the density of oxygen; 1.251, of nitrogen; 1.9769, of carbon dioxide; 0.179, of helium; and 1.293, of air. The density of a gas is directly proportional to the pressure exerted by it (Boyle's law) and inversely proportional to its absolute temperature (Charles' law).

3. *Compressibility*

The property of compressibility is almost exclusively an attribute of gases. It describes the ready alteration of the average intermolecular distances in gases on the application of force and is an essential expression of the kinetic concept of the structure of matter. When a gas is compressed, if the temperature remains the same, the pressure rises in proportion to the increase in the number of molecules per unit volume. This change in pressure is identical with a change in density since the weight per unit volume has increased in the same proportion. The converse relation is true on rarefaction of a gas.

If now we compare a column of gas molecules to a column of bricks it is apparent that each unit will bear the weight of all above it in some manner. The downward force exerted on any brick can be described by its position below the top one, in terms of the unit weight of a brick, and the number of bricks above this one; the next below it bears this force plus one brick more, and so on. The density of the brick clay is constant because it is a solid. In the gas there is a relatively large distance between molecules, which decreases as the force exerted on them increases. Even though there is probably no more than one contact per molecule on the average at any one instant, the structure is maintained by the molecules shuttling up and down until they strike the next adjacent one (disregarding for the moment all components to the sides). In such a column the number of molecules per unit height is greater at the bottom than at the top

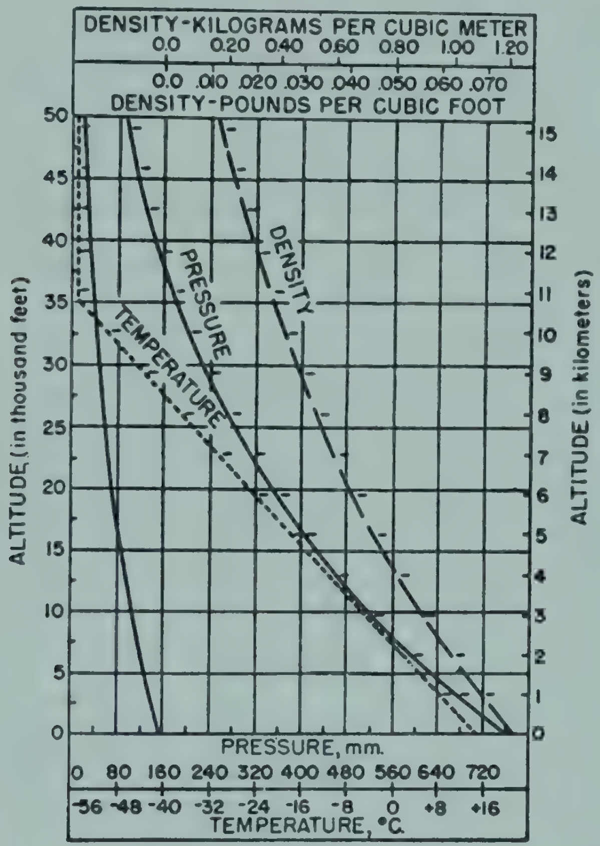

Figure 1. Standard atmosphere chart officially adopted by all interested United States Government organizations for aeronautics and related purposes.[8] The values for the temperature, pressure, and density at all altitudes agree closely with the yearly average of United States meteorological data at 40° North Latitude. See National Advisory Committee for Aeronautics, *Tech. Repts.* 147, 218, and 246 for formulas and complete tables.

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[8] W. G. Brombacher, Standard atmosphere chart, *Natl. Bur. Standards Misc. Pub.* No. **82**, 1927.

and it follows that the density is changed accordingly. This means that to ascertain the weight of the gas lying above, at any level, we must add the weights of a series of units of gas each a little lighter than the unit below it. The rate of decrease in weight of these units can be roughly described as logarithmic and this determines the shape of the curve drawn through the atmospheric pressure values at different altitudes. Figure 1ᵃ shows this relation when the proper corrections are included for the known average temperature of the air at the various altitudes and for other factors of real but minor importance.

From Figure 1 it can be seen that the atmospheric pressure is reduced to one half at about 17,500 feet, to one quarter at about 33,500 feet, and so on. Actually some 99 per cent of the atmosphere is contained in the lower 18 to 19

TABLE 1

Altitude-Pressure-Temperature Table for 500-Feet Intervals Ranging from −1000 to 80,000 Feet[a]

Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.	Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.
	in. Hg	mm. Hg				in. Hg	mm. Hg		
−1,000	31.02	787.9	17.0	16.0	15,500	16.54	420.2	−15.7	−0.6
−500	30.47	773.8	16.0	15.5	16,000	16.21	411.8	−16.7	−1.2
					16,500	15.89	403.5	−17.7	−1.7
0	29.921	760.0	15.0	15.0	17,000	15.56	395.3	−18.7	−2.2
500	29.38	746.4	14.0	14.5	17,500	15.25	387.3	−19.7	−2.7
1,000	28.86	732.9	13.0	14.0	18,000	14.94	379.4	−20.7	−3.2
1,500	28.33	719.7	12.0	13.5	18,500	14.63	371.7	−21.7	−3.7
2,000	27.82	706.6	11.0	13.0	19,000	14.33	364.0	−22.6	−4.3
2,500	27.31	693.8	10.0	12.5	19,500	14.04	356.5	−23.6	−4.8
3,000	26.81	681.1	9.1	12.0					
3,500	26.32	668.6	8.1	11.5	20,000	13.75	349.1	−24.6	−5.3
4,000	25.84	656.3	7.1	11.0	20,500	13.46	341.9	−25.6	−5.8
4,500	25.36	644.2	6.1	10.5	21,000	13.18	334.7	−26.6	−6.3
					21,500	12.90	327.7	−27.6	−6.9
5,000	24.89	632.3	5.1	10.0	22,000	12.63	320.8	−28.6	−7.4
5,500	24.43	620.6	4.1	9.5	22,500	12.36	314.1	−29.6	−7.9
6,000	23.98	609.0	3.1	9.0	23,000	12.10	307.4	−30.6	−8.4
6,500	23.53	597.6	2.1	8.5	23,500	11.84	300.9	−31.6	−9.0
7,000	23.09	586.4	1.1	8.0	24,000	11.59	294.4	−32.5	−9.5
7,500	22.65	575.3	0.1	7.5	24,500	11.34	288.1	−33.5	−10.0
8,000	22.22	564.4	−0.8	7.0					
8,500	21.80	553.7	−1.8	6.5	25,000	11.10	281.9	−34.5	−10.5
9,000	21.38	543.2	−2.8	6.0	25,500	10.86	275.8	−35.5	−11.1
9,500	20.98	532.8	−3.8	5.5	26,000	10.62	269.8	−36.5	−11.6
					26,500	10.39	263.9	−37.5	−12.1
10,000	20.58	522.6	−4.8	5.0	27,000	10.16	258.1	−38.5	−12.7
10,500	20.18	512.5	−5.8	4.5	27,500	9.94	252.5	−39.5	−13.2
11,000	19.79	502.6	−6.8	4.0	28,000	9.72	246.9	−40.5	−13.7
11,500	19.40	492.8	−7.8	3.5	28,500	9.50	241.4	−41.5	−14.3
12,000	19.03	483.3	−8.8	2.9	29,000	9.29	236.0	−42.5	−14.8
12,500	18.65	473.8	−9.8	2.4	29,500	9.08	230.7	−43.4	−15.3
13,000	18.29	464.5	−10.8	1.9					
13,500	17.93	455.4	−11.7	1.4	30,000	8.88	225.6	−44.4	−15.9
14,000	17.57	446.4	−12.7	0.9	30,500	8.68	220.5	−45.4	−16.4
14,500	17.22	437.5	−13.7	0.4	31,000	8.48	215.5	−46.4	−16.9
					31,500	8.29	210.6	−47.4	−17.5
15,000	16.88	428.8	−14.7	−0.1					

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[a] W. G. Brombacher, Altitude-pressure tables Based on the United States Standard Atmosphere, *Nat'l. Advisory Comm. for Aeronaut. Rept.* No. **538** (republished 1942).

TABLE 1 (*continued*)

Altitude, ft.	Pressure		Temperature, °C.	Mean temperature, °C.
	in. Hg	mm. Hg		
32,000	8.10	205.8	−48.4	−18.0
32,500	7.91	201.0	−49.4	−18.6
33,000	7.73	196.4	−50.4	−19.1
33,500	7.55	191.8	−51.4	−19.6
34,000	7.38	187.4	−52.4	−20.2
34,500	7.20	183.0	−53.4	−20.7
35,000	7.04	178.7	−54.3	−21.3
35,332	6.93	175.9	−55.0	−21.6
35,500	6.87	174.5	−55.0	−21.8
36,000	6.71	170.4	−55.0	−22.3
36,500	6.55	166.4	−55.0	−22.8
37,000	6.39	162.4	−55.0	−23.3
37,500	6.24	158.6	−55.0	−23.8
38,000	6.10	154.9	−55.0	−24.3
38,500	5.95	151.2	−55.0	−24.8
39,000	5.81	147.6	−55.0	−25.2
39,500	5.68	144.1	−55.0	−25.6
40,000	5.54	140.7	−55.0	−26.0
40,500	5.41	137.4	−55.0	−26.4
41,000	5.28	134.2	−55.0	−26.8
41,500	5.16	131.0	−55.0	−27.2
42,000	5.04	127.9	−55.0	−27.6
42,500	4.92	124.9	−55.0	−28.0
43,000	4.80	122.0	−55.0	−28.3
43,500	4.69	119.1	−55.0	−28.6
44,000	4.58	116.3	−55.0	−29.0
44,500	4.47	113.5	−55.0	−29.3
45,000	4.36	110.8	−55.0	−29.6
45,500	4.26	108.2	−55.0	−29.9
46,000	4.16	105.7	−55.0	−30.2
46,500	4.06	103.2	−55.0	−30.5
47,000	3.97	100.7	−55.0	−30.8
47,500	3.873	98.38	−55.0	−31.1
48,000	3.781	96.05	−55.0	−31.4
48,500	3.693	93.79	−55.0	−31.7
49,000	3.605	91.57	−55.0	−31.9
49,500	3.520	89.41	−55.0	−32.2
50,000	3.436	87.30	−55.0	−32.4
51,000	3.276	83.22	−55	—
52,000	3.124	79.34	−55	—
53,000	2.978	75.64	−55	—
54,000	2.839	72.12	−55	—
55,000	2.707	68.76	−55	—
56,000	2.581	65.55	−55	—
57,000	2.460	62.49	−55	—
58,000	2.346	59.58	−55	—
59,000	2.236	56.80	−55	—
60,000	2.132	54.15	−55	—
61,000	2.033	51.63	−55	—
62,000	1.938	49.22	−55	—
63,000	1.847	46.92	−55	—
64,000	1.761	44.73	−55	—
65,000	1.679	42.65	−55	—
66,000	1.601	40.66	−55	—
67,000	1.526	38.76	−55	—
68,000	1.455	36.95	−55	—
69,000	1.387	35.23	−55	—
70,000	1.322	33.59	−55	—
71,000	1.261	32.02	−55	—
72,000	1.202	30.53	−55	—
73,000	1.146	29.10	−55	—
74,000	1.093	27.75	−55	—
75,000	1.041	26.45	−55	—
76,000	0.993	25.22	−55	—
77,000	0.946	24.04	−55	—
78,000	0.902	22.92	−55	—
79,000	0.860	21.85	−55	—
80,000	0.820	20.83	−55	—

miles of the gaseous envelope of the earth, and only about the lower 2 miles of it are habitable without marked restrictions to warm-blooded animals.[6]

The pressure exerted by the weight of the atmosphere is exerted radially at any one point in proportion to the amount of overlying gas, as discussed above, and it is ordinarily measured by utilizing the fact that the atmosphere will support the weight of a column of fluid (oil, water, mercury, etc.) of a length inversely proportional to its specific gravity. Thus the standard atmosphere at sea level will support a column of mercury 760 mm. in length, and this is known to exert a pressure of 14.66 p.s.i. It is customary for the sake of convenience to use the height of such a barometer as a measure of atmospheric pressure.

It is apparent that the increased pressures in the open atmosphere follow extensions of the relations discussed above for conditions at altitude; in fact the altitudes shown in Table 1 are extended to −1000 feet to facilitate calculations for depressions. On the other hand, the more generally practical use of increased pressures is in connection with the displacement of water while diving and of water and solids (such as sand and mud) in caisson work. In these cases the weight of the air becomes a constant and usually negligible factor upon which is superimposed the pressure exerted by the column of fluid above the free surface in such an enclosed system. In diving a uniform, or arithmetic, increment in pressure per unit depth is added on descent. Due to the relatively moderate depths that can be withstood in diving, and the nearly incompressible nature of fluids, this increment is practically constant. In sea water it is about 1 atm. for every 33 feet, or roughly $^1/_2$ p.s.i. per foot.

4. Partial Pressures

The pressure changes described above are shared by the constituent gases of the atmosphere in the ratio of their occurrence (Dalton's law) in air, or as modified in any gas space, such as the alveoli of the lungs. This situation follows from the kinetic concept of gases, since each species of molecule exerts its pressure throughout any definable space as if it were there alone. Thus, $P(\text{air}) = p'\text{N}_2 + p''\text{O}_2 + p'''\text{H}_2\text{O} + p''''$ inert gas, etc., where $P(\text{air})$ is the barometric pressure and p', p'', and so forth, are the partial pressures of the several gases of the air. (Certain deviations from this simple relation may be expected under high positive pressures due to interference of different molecular species with each other.) Any change in the sum of these component pressures must be shared proportionately by the constituents. Thus, a curve describing the partial pressure of oxygen in air at different altitudes would be the line drawn about one fifth the distance from the ordinate axis for air pressure at any altitude in Figure 1. It will be seen later that the partial pressure of gases is most important in the physiology of gaseous exchange and actually forms the nucleus of all rational approach to the problems of the effects of abnormal atmospheric pressures upon living organisms.

The pressure-volume relationship of gases at constant temperature at any altitude is determined from Boyle's law (PV = constant) by the relation $P_1V_1 = P_2V_2$. By suitable arrangement the volume assumed by wet air at constant temperature at any altitude is calculable from the formula[10,11]

$$V_2(\text{wet}) = V_1(\text{wet})\frac{P^1 - p\text{H}_2\text{O}}{P_2 - p\text{H}_2\text{O}}$$

where the symbols have the following significance: V_1 = the initial volume at ground level, V_2 = the resulting volume at altitude of the same weight of gas as contained in V_1, P_1 = the initial pressure at ground level, P_2 = the resulting

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[10] C. H. Fugitt, *U. S. Naval Air Training Bases, Pensacola, Fla.*, Project X-[illegible], Rept. No. **1** (1945).

[11] Aero Medical Laboratory Staff, *AAF Manual* No. **25-2** (March, 1945).

pressure at altitude, and pH_2O = the vapor pressure of water at the specified temperature.

5. *Solubility or Absorption*

To a greater or lesser extent all gases are soluble in other substances and, barring for the moment chemical reaction with the solvent, the concentration of gas dissolved is proportional to its pressure (partial pressure) above the interface of gas and solvent (Henry's law). The rate of solution depends on the difference between the frequency at which the gas molecules impinge on the surface and that at which the gas in solution tends to escape from solution, and on the nature of the solvent.

These facts are equally true of gases dissolved in body substances. The living organism exists in a state of dynamic equilibrium with the gases that impinge upon it.[12] The diffusion of gases through the outer skin of the body is of a low order, as shown by Behnke and Willmon.[13] As far as practical considerations require, the gaseous exchange of the body is through the lung surface, where solution is effected readily.

It has been shown by Haldane[14] and others that the volume of oxygen passed by a human lung–blood interface per mm. Hg differential pressure (across the interface) varies from 25 to 56 ml. per minute, depending on the state of exercise. For carbon dioxide the value is at least 20 to 30 times as great. This ratio is fortuitously equal but unrelated to that of their solubilities in water at equilibrium, and actually depends on factors affecting diffusivity.[15]

The greater solubility in water of carbon dioxide, as compared with oxygen, is due mainly to its tendency to form a hydrate with water and to ionize in solution. This tendency acts to decrease the partial pressure of carbon dioxide in the water and thus to maintain a greater difference in concentration across the interface than can be effected with inert gases.

As implied above, the solution of gases in the body is primarily a solution in water, and after this initial action further distribution depends on the diffusion, circulation, partition, and chemical combination, if any, in other body substances. Other than the blood and watery fluids the most important gas reservoir of the body is its fat, since fat occurs in a relatively large quantity. Gas dissolved in fat has been shown by Behnke,[16] Gersh,[17] and others to be a major source of difficulty in caisson disease. Table 2 shows the solubilities of several atmospheric gases in water and olive oil and the ratio of these solubilities, indicating that at

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[12] J. Sendroy, Jr., R. T. Dillon, and D. D. Van Slyke, *J. Biol. Chem.*, **105**, 597 (1934).

[13] A. R. Behnke and T. L. Willmon, *Am. J. Physiol.*, **131**, 627 (1940–41).

[14] J. S. Haldane and J. G. Priestley, *Respiration*. Yale Univ. Press, New Haven, 1935.

[15] J. Verduin, *Science*, **121**, 215 (1955).

[16] A. R. Behnke, *Bull. New York Acad. Med.*, **18**, 561 (1942).

[17] I. Gersh and G. E. Hawkinson, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **1** (1944).

TABLE 2

Solubility of Atmospheric Gases in Water and Olive Oil at 28° C.[16]

Gas	Solubility (ml./ml.)		Oil-water ratio
	Water	Olive oil	
Oxygen	0.023	0.112	4.9 :1
Nitrogen	0.0127	0.0667	5.24:1
Helium	0.0087	0.0148	1.7 :1
Argon	0.026	0.1395	5.32:1

equilibrium a large amount of gas may be stored in the fatty tissues. The role of fat in aeroembolism is similar to that in decompression sickness. More will be said of it in the following sections. As far as other substances in the body are concerned, the capacity of the body for simple solution of gases is almost wholly due to the water or fat content, and no further distinction need be made here for this property.

The solution of gases in the body, including oxygen and carbon dioxide, was not readily analyzed by experiment until recently, although much work on the use of gases for estimating cardiac output and lung function is in the literature. The converse, or desaturation, has been studied intensively in developing a means of obviating caisson disease and aeroembolism. Data on nitrogen elimination[16,18] are shown graphically in Figure 2 and indicate the involvement of a system of at least two components; fat and water, for which an empirical approximation was developed. It has been shown further by Smith and Morales[19,20] that

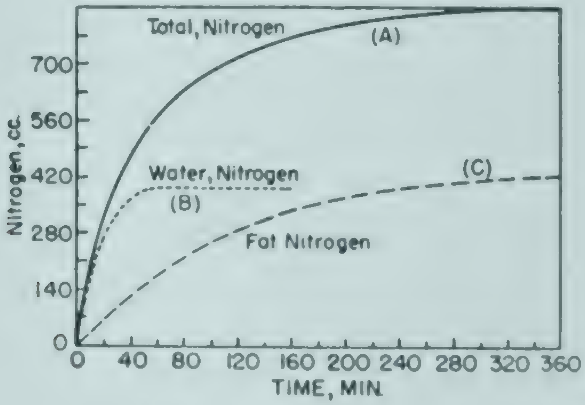

Figure 2. Elimination curve for nitrogen.[20] Total nitrogen (A) represents the average of the values for nitrogen elimination from three men (average weight 64 kg.) who breathed pure oxygen at atmospheric pressure. Water nitrogen (B) and fat nitrogen (C) are hypothetical curves showing the absorption or elimination of nitrogen by the body solvents. The values for nitrogen on (A) are approximately the sum of corresponding values on (B) and (C).

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[18] L. A. Shaw, A. R. Behnke, A. C. Messer, R. M. Thomson, and E. P. Motley, *Am. J. Physiol.*, **112**, 545 (1935).

[19] R. E. Smith and M. F. Morales, *Bull. Math. Biophys.*, **6**, 125 (1944).

[20] R. E. Smith and M. F. Morales, *Bull. Math. Biophys.*, **6**, 133 (1944).

certain refinements in the consideration of physical constants of the various media for the accumulation of gases, the avenues of saturation and desaturation, and so forth, enable them to set up a general theoretical expression for the gain or loss of gases from the whole or any portion of the body. They consider the effects of blood volume, blood flow, tissue volume, surface presented, permeability, solubility, and gas concentration. This analysis is shown in Figure 3 to fit well with experimental data, and it is apparent that a rational and basically sound relation has been developed.

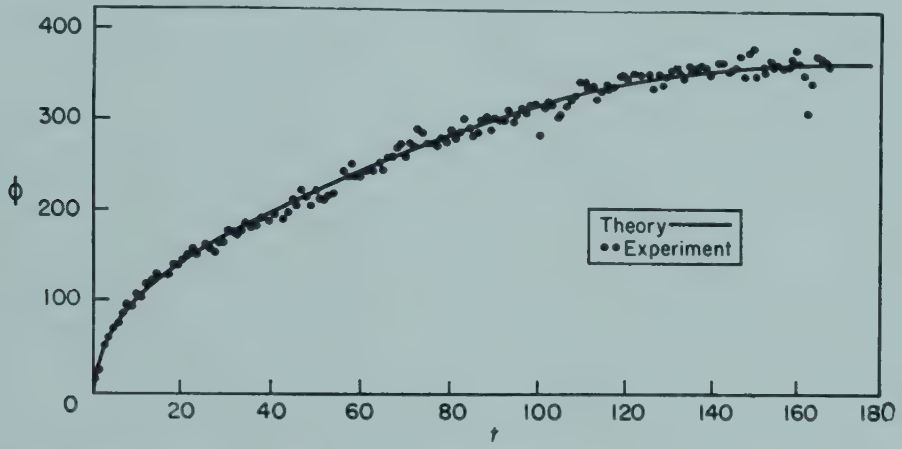

Figure 3. Total nitrogen gas uptake by limb tissues.[20] ϕ, a function of total nitrogen absorbed at any time t, is the counts of radioactive krypton at one minute intervals.

6. Temperature of the Atmosphere, Its Origin and Variation

Since we are dealing generally with body temperature under conditions of reasonable functional integrity, it would not seem that the environmental temperature plays any major role in the response to atmospheric pressure change. The greatest variation in body temperature lies probably between 28 and 40° C. In this range the solubility of gases generally falls with increased temperature, though the magnitude of the change is relatively small. The temperature coefficient of simple chemical reactions *in vivo* is found to be of a moderate order and is given by the Arrhenius relation, which states that the rate of reaction is doubled or trebled for every 10° C. rise.[21]

On the other hand, certain physiological responses to temperature changes of very minor extent are exceedingly marked and important to the economy of gases in the body, though by indirection. A consideration of atmospheric temperature variation must be included here to be drawn upon later in explanation of certain responses to alterations in pressure at altitude.[22]

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[21] H. L. Blum, *Photodynamic Action and Diseases Caused by Light.* Reinhold, New York, 1941.

[22] H. G. Armstrong, *Military Surgeon,* **79,** 133 (1936). H. G. Armstrong, *Principles and Practice of Aviation Medicine.* Williams & Wilkins, Baltimore, 1938.

The temperature of the atmosphere is due mainly to the energy absorbed from solar radiation, secondarily to that added by conduction or convection. For our consideration, the distribution of temperature in the two zones of the atmosphere nearest the earth is of interest. From the ground up to about 36,000 feet there is found a variable temperature, the average value falling off with increase in altitude, and above this level there is a region of uniform temperature known as the isothermal layer. This uniform temperature, which extends to excessively high altitudes, is reported to be relatively constant at —55° C. (—67° F.).[5] It is in this upper region that the ozone produced by absorption of ultraviolet radiation by oxygen in the outer layers is observed to gravitate in appreciable concentration. Because of the filtering action of these superior strata there is relatively little absorption of energy by the gases in the isothermal layer. Below the lower boundary of this layer, at about 36,000 feet, water vapor and solids in the atmosphere absorb energy in an appreciable amount, and the temperature rises gradually as the earth is approached until the characteristic temperature of the latitude is attained. On the other hand, owing to thermal displacement of air masses by convection and conduction of heat and by the absorption of reradiated energy from the earth's surface, there is often a great deal of random distribution of temperature. Thus, surface temperature may be colder than at several thousand feet directly above the ground, and several such inversions may be found above each other. These are found mainly over land masses and are part and parcel of the "weather." The mechanism is not important to this discussion. Further details may be found in Humphreys.[5] Local temperatures below the tropopause, or lower stratosphere level, as low as —120° F. have been recorded. It is important to point out that in contradistinction to the previous fact, aeronautical tables are calculated on the assumption that there is a constant temperature in the so-called isothermal region and that a regular increase in temperature on descent from this level to the ground is found. Thus the effect of the temperature variations on "pressure altitudes" in the atmosphere is of interest to the physiologist, who is concerned with the barometric value of any linear altitude and not with the actual height above sea level.

As far as increased pressures are concerned, it is evident that, except for heat added by compressing equipment, the temperature of the air or other gases will tend to equal that of the environment; for example, in sea water it will range upward from 28.6° F., which is the freezing point of sea water of average salinity.

While the heat conductivity of gases is not affected by pressure, certain changes in heat loss from the body are to be expected from changes in pressure of the atmosphere, since the heat capacity of the air is changed and tends to alter the temperature differential necessary to maintain constant heat transfer from the body to the environmental gases. This effect is very marked for subjects in low pressure chambers at "altitude," and may cause wrong interpretation of the temperature sensations.

C. CHEMICAL ACTIVITY

The chemical activity of the gases of the atmosphere relevant to the physiology of atmospheric pressure in mammals is limited to that of oxygen and carbon dioxide. This limitation is mainly due to the fact that the energy levels needed for direct chemical reaction are not feasible in living systems. All reactions of gases depend, under these circumstances, either primarily or secondarily on catalysis of some type. The metabolic involvement of hydrogen and nitrogen has been substantiated for living forms as high as bacteria,[23,24] but mammals have not been found to possess the systems necessary for either hydrogen or nitrogen activation in the gaseous state. Enzymes for the activation of gaseous oxygen and carbon dioxide are integral to the metabolic process of all mammals.[25] In common with reactions of other substances, the rate and equilibrium of the reaction of gases depend, among other factors, on the concentration of the gas, both relatively and absolutely; that is, the systems are pressure-labile within limits. This property is of utmost importance in the physiological analysis of the effects of atmospheric pressure.

In setting aside, at the beginning of Section B.*5*, the fact that chemical reaction affects the solution of gases, it was intended only to reserve this complication for further discussion because, as will be seen in subsequent sections, it is of great importance in the exchange of gases between the atmosphere and the body fluids.

It may be fitting to point out at this time that the widely publicized,[26] similarity between the status of flames and metabolic oxidations at altitude is a fallacious one, flames having actually only minor response to even extensive pressure changes but being markedly sensitive to relative concentration, while metabolic oxidations behave quite the opposite. The difference is in part due to the fact that in metabolic activities there exists always a solution phase between the free gas and the substance oxidized. Contrary to popular accounts[26,27] a candle flame will continue to burn in air up to a simulated altitude of 57,000 feet, provided a large enough volume of air is used for the environment of the flame. A change in the character of flames at altitude[6] led to erroneous conclusions from experimental engineering data cited above.[28] The ultimate limitation on flame stability in the case of the candle results from the flame's being

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[23] Alec H. Laurie, *Discovery Repts.*, **7,** 365 (1933).

[24] A. Krogh, *Nature,* **133,** 635 (1934).

[25] C. L. Evans, *Starling's Principles of Human Physiology*. 8th ed., Lea and Febiger, Philadelphia, 1941.

[26] *Life,* **12,** No. 8, 66 (1942).

[27] H. G. Armstrong and M. C. Grow, *Fit to Fly, a Medical Handbook for Fliers*. Appleton-Century, New York, 1941.

[28] W. S. Weeks and R. K. Byerts, *Eng. Min. J.,* **141,** No. 10, 44 (1940).

forced to recede from the wick in order to carry a sufficient quantity of oxygen to the flame front. Not only is vaporization of the fuel of the candle flame progressively inhibited, but also the flame literally blows itself out. It has, however, been possible to maintain hydrogen flames in air at altitudes somewhat in excess of that for the candle flame since combustion of hydrogen is not dependent on the melting and vaporization of the fuel by the heat of the flame.[29]

While relatively few data are at hand to indicate the quantitative effect of increasing atmospheric pressure on the metabolism of living systems, effects of oxygen and carbon dioxide at high pressure[30] indicate that marked influences on metabolism do occur.

1. *Oxygen and Carbon Dioxide*

The pressure-labile chemical combination of oxygen and carbon dioxide with the blood is a reciprocal relation involving the binding power of hemoglobin and bases in the blood complex for these two gases of the atmosphere. Essentially there is an involved chemical redistribution of ions between blood plasma and tissue solutes[31] for every change in partial pressure of the constituent gases. Under conditions of normal atmospheric pressure these relations are given by curves shown in Figures 4 and 5.[32] Further codification of these relationships

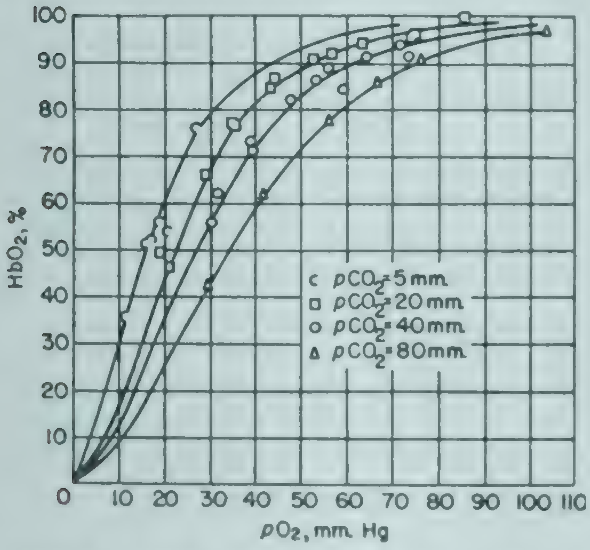

Figure 4. Oxygen dissociation curves of blood of a man at work.[32]

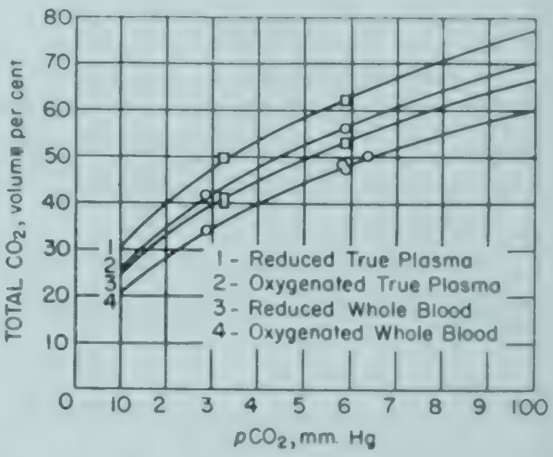

Figure 5. Carbon dioxide dissociation curves of blood of a man at work.[32]

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[29] From unpublished data of the author.

[30] J. W. Bean, *Physiol. Revs.*, **25**, 1 (1945).

[31] A. V. Bock, H. Field, Jr., and G. S. Adair, *J. Biol. Chem.*, **59**, 353 (1924).

[32] A. V. Bock, D. B. Dill, L. M. Hurxthal, J. S. Lawrence, T. C. Coolidge, M. E. Dailey, and L. J. Henderson, *J. Biol. Chem.*, **73**, 749 (1927).

between the multiple factors known to affect this system has been developed by Henderson and his associates,[33] but for the present purpose these need not be discussed here in detail. It is sufficient to point out that, since dependence on partial pressure of the gases has been established, the relationship holds regardless of the external cause of the change in partial pressure.

Therefore, in the case of oxygen it is possible to interpret the partial pressure axis of the dissociation curve for hemoglobin in terms of altitude. In this case a correction for converting the atmospheric partial pressure to that actually found at the alveolar surface must be made. Figure 6 shows theoretical and equilibrium values for both carbon dioxide and oxygen pressures at the lung-blood interface at different altitudes. The deviations of the experimental data are due mainly to compensations of the body and not to the simple chemical relationships of the gases and their absorbent substrates.[34]

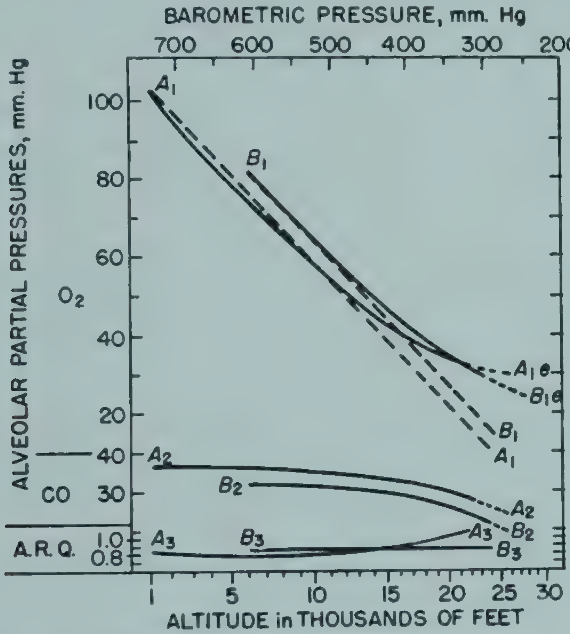

Figure 6. Effect of decreasing pressure on alveolar oxygen and carbon dioxide partial pressures.[34] Curves A_1e, A_2, and A_3: average of experimental data, subjects acclimatized to 1000 feet (300 meters). Curves B_1e, B_2, and B_3: average of experimental data, subjects acclimatized to 6200 feet (1900 meters). Curves A_1 and B_1: theoretical fall in oxygen partial pressure with no increased ventilation. A.R.Q. = alveolar respiratory quotient.

2. "Inert" Gases

In contrast to the properties of chemically active gases as discussed above, the behavior of the so-called inert gases of the atmosphere, such as nitrogen, argon, and krypton, is usually thought to be purely physical. Certainly under vital conditions in mammals there is no corroborated evidence that nitrogen gas can enter into chemical reactions.[24] On the other hand, observations at high positive pressures, by Behnke and Yarbrough[35] and others, have led to the postulation of a quasi-physical or chemical action that may be involved in the production of a "narcosis" under these conditions by nitrogen and argon and not by the lighter gases such as helium and hydrogen.[36] There does not seem to be at present any known cause for these effects except that the behavior of gases does not follow the usual relations when high pressures exist. Recently similar observations have been made at atmospheric pressure with xenon and argon[37] and helium and argon[38,39] in both man and lower animals.

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[33] L. J. Henderson, A. V. Bock, H. Field, Jr., and J. L. Stoddard, *J. Biol. Chem.*, **59**, 379 (1924). L. J. Henderson, *Blood*. Yale Univ. Press, New Haven, 1928.

[34] W. R. Boothby, *Proc. Staff Meetings Mayo Clinic*, **20**, 209 (1945).

III. Effects of Increased Atmospheric Pressure on the Body

A. CHARGING OF THE BODY WITH GASES

1. Mechanical Effects

Mechanical effects of compression of the environmental gases on the fluid and solid constituents of the living system are negligible because of the incompressibility of these constituents. On the other hand, since pressure is transmitted undiminished throughout these substances of the body, displacement of fluid or tissue into any gas space not continuous with the atmosphere is unavoidable. Such gas spaces are, unfortunately for those concerned, present in the body, particularly in the middle ear and various sinuses in the head; of lesser importance are the included abdominal and other gases.

In general the mechanical effects in natural diving are only quantitatively different from those in caisson diving, while suit diving adds a mechanical hazard called "the squeeze," which is really a macroscopic extension of the above principle, in that here the body is forced into the helmet if air pressure fails to balance water pressure. It is of considerable practical importance because collapse of the lungs with massive congestive hemorrhage results quite early in such cases.

The middle ear, including the mastoid sinus, has only intermittent connection with the external atmosphere through the soft-walled eustachian tube. On compression the eardrum and this pharyngeal structure, which is normally collapsed up to the point where it is enclosed in the bony structure of the head and thus forms a stopper, are pushed progressively inward. If voluntary opening of this tube is not affected by movement of the adjacent muscles during swallowing, then continued increase in pressure causes a displacement of the eardrum into the lumen of the middle ear with varying degrees of trauma, and, more importantly,

[35] A. R. Behnke and O. D. Yarbrough, *U. S. Naval Med. Bull.*, **36,** 549 (1938).
[36] E. M. Case and J. B. S. Haldane, *J. Hyg.*, **41,** 225 (1941).
[37] J. H. Lawrence *et al.*, *J. Physiol.*, **105,** 197 (1946).
[38] S. F. Cook, *J. Cellular Comp. Physiol.*, **36,** 115 (1950).
[39] S. F. Cook *et al.*, *Am. J. Physiol.*, **164,** 248 (1951).

the displacement of blood into the capillary lining of this cavity, resulting in transient reddening, petechial and massive hemorrhage, and occasionally rupture of the tympanum.[40] In addition, there is an early dulling of the hearing, which is due to the marked displacement of the incus, malleus, and stapes, preventing them from transmitting sound vibrations to the middle ear properly. According to the experience of the Royal Navy[41] it is found that some degree of acute drum trauma is produced in all but the most experienced pressure workers.

The action of increased atmospheric pressure on the various sinuses is only deleterious and painful when, as in the ear, the openings are not patent. In normal individuals this is rare, but it is a chronic condition with some individuals, generally associated with infection or malformations. Obviously, acute infection of the upper respiratory tract tends to produce this condition. When the openings of the sinuses are thus occluded, an increase in atmospheric pressure will result in severe pain and varying degrees of trauma even with moderate pressure differences. This seeming disproportionality between cause and effect is due possibly to the rather large surface-to-volume ratio of most sinuses, allowing ready distension of large areas of capillaries. This distention leads to marked stimulation of deep pain receptors, with the observed sequelae of nausea, etc., due to autonomic discharge from this stimulation. As far as can be determined, reports from the older literature of mechanical trauma to the vascular system are to be attributed more to the various conditions enumerated above than to other gross hydraulic effects, as was formerly held.[42] It is true, however, that the blood is forced into the capillaries lining any such rigid-walled, isolated gas space and, depending on the tonic state, may result in hemorrhage. If we assume a normal capillary pressure of 40 mm. Hg, it takes only $^1/_{19}$ atm. of positive pressure to double this value in the capillary bed of the ear or sinus. Clinical tests of capillary fragility are based on petechial hemorrhages in normal tissue with 50 mm. Hg pressure above normal![25]

Gases in the alimentary tract are, wherever located, subject to compression by body tissues and for the most part do not cause any inconvenience beyond the displacement of the viscera, which in most cases can be of only a benign nature. As will be shown subsequently, this does not absolve these gas entities from consideration since, unless passed as flatus, they expand on decompression.

There remains one more mechanical effect of compression that, while rare, is real and may produce drastic sequelae: this concerns the compression of the gases in the lungs. Offhand, no effect would be expected since almost continuous patency of the breathing passages is assumed. It must be recognized, however, that, during rapid compression, closure of the glottis in swallowing or breath holding may result in compression of the lungs to such an extent that only with considerable difficulty can sufficient positive pressure be created by the thoracic musculature to release the glottal closure. Such cases have been observed on recompression from negative pressure, as will be discussed later. It is important, especially in experimental work, that warning against breath holding be promulgated during indoctrination and in the course of work while rapid compression is being effected.

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[40] E. D. D. Dickson, J. E. G. McGibbon, and A. C. P. Campbell, *J. Laryngol. Otol.*, **58**, 465 (1943).

[41] *Roy. Naval Med. Bull.* No. **5**, 13 (1943). Abst. in *Bull. War Med.*, **4**, 305 (1944).

[42] E. C. Hoff, *A Bibliographical Source-Book of Submarine and Compressed Aid Medicine.* U. S. Government Printing Office, Washington, D. C., 1947.

Other effects of compression that are partly of a mechanical nature, such as the transient accumulation of carbon dioxide in the lungs and blood during inflow of gas on rapid compression of the atmosphere, as described by Bean,[30] are discussed under subsequent headings.

The extension of mechanical effects to conditions of pathology is not possible in this presentation, but reports of injury to pathological areas in the lungs on compression are found in the literature[30] and argue strongly for thorough preemployment medical examinations in occupations involving atmospheric pressure changes.

2. Solution of Gases in the Body

As indicated in the section on the solubility of atmospheric gases, the capacity of the blood and tissues for taking up gases is determined by two general characteristics that respond to partial pressure. That is, both the simple physical solution of gases in fluids and the pressure-labile chemical association of certain of them with solutes in the fluids and their cells are concomitantly affected by changes in pressure. Relatively small quantities of gas are taken up by the watery portion of the blood, as is seen from Table 2, but it must be kept in mind that all gases passing to and from the tissues pass through the solution phase in the course of their transfer between tissue and atmosphere. In addition, at every stage of the transfer of gases there is, inescapably, a series of mediums through which gas exchange takes place, each of which has its own coefficient of diffusion, permeability, partition, and the like, which set up the parameters of the tissue-gas relationship with external pressure.

Smith and Morales[43] describe at least four phases in the attainment of saturation of tissues with inert gases by way of the lungs. Their analysis gives a curve of uptake with respect to time that, instead of having a uniformly changing slope, is characterized by an inflection or flattening in what they call the second stage of gas transfer. At this time the blood is taking in gas at a uniform rate, since it is presented at the lung surface at a limited rate, in conformity with the speed of circulation. These transient phenomena are of interest here mainly in that they show the system to be first serially, then concomitantly, affected by gas pressure changes during an increase in pressure. It is evident, further, that by virtue of these limiting phases the degree of saturation or concentration of gases in the tissues is limited with respect to time.

Although the general nature of the uptake of gases in the different tissues of the body is similar, the effectiveness of the distributing system varies and this further affects the time required for saturation. The partition of gases among fatty, glandular, neural, and muscular tissues is obviously dependent at equilibrium on the solubility of the gases in the various materials comprising the cell structures, the protoplasm, and the inclusions, but at any time short of equilibrium the major factors other than those controlling diffusion (i.e., invasion and evasion of gases)[15] may be considered to be the transport and access of the gases to the cells. These factors are usually spoken of as the vascularization of the tissue. Gersh[44] has shown that the ratio of capillary surface to the total cell volume of fatty tissues is 51.9 and of tissues poor in fat is 222.2. He indicates further that this disparity is due to the included fat alone, since the same ratio on the basis of volume of active protoplasm exceeds that found for muscle.

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[43] R. E. Smith and M. F. Morales, *Bull. Math. Biophys.*, **6**, 141 (1944).

Essentially it is seen that the fat depots are large nitrogen reservoirs with restricted access and thus require a longer time for charging than do the lean tissues.

3. Rate of Change of Pressure

The foregoing facts indicate that complete saturation requires a definite lapse of time, and thus on theoretical grounds alone short deep dives may be effected with less chance of sequelae due to excess inert gas than may long shallow dives. From experience and experimentation the relations of these pressure and time factors have been summarized in diving tables.[45,46]

The immediate effects limiting the rate of compression are mainly those of a mechanical nature on the ears, sinuses, and other isolated gas phases within the body. Gastrointestinal gases apparently play no role in compression but should be taken into account in view of the ultimate decompression. The effects on the ear and sinuses are not expressible in quantitative form because of the highly individual nature of the response.

The only indication that rapid compression may have some other limiting factor is in the observation of Bean[30] that the influx of gas into the lungs may cause a transient retardation of the CO_2 elimination and thus temporarily elevate the pCO_2 both in the alveoli and blood-tissue complex. Bean found complete arrest of alveolar gas outflow in human subjects during such rapid compression, and reports elevation of pCO_2 in catheterized lungs of dogs under anesthesia.

B. EFFECTS OF MAINTAINED POSITIVE ATMOSPHERIC PRESSURE

1. State of Saturation of the Several Body Tissues

The diving tables[46] indicate that saturation at any level is rarely attained in the course of the recommended bottom period since the time schedule for decompression increases throughout with increased stay at the working level. The phenomenally long decompressions necessary for even short stays at great depths prove to be a limiting factor in the amount of useful work that can be effected, even under the best possible conditions; for example, a 20-minute dive of 300 feet on compressed air requires a total time of 3 hours.

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[44] I. Gersh and M. A. Still, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **III** (1944).

[45] R. L. Fisher and W. A. White, Jr., *Naval Med. Research Inst., Rept.* No. **86** (1944).

[46] *Diving Manual, 1943.* Navy Dept., Bureau of Ships, U. S. Government Printing Office, Washington, D. C.

The limitations on the stay at working level are, however, legion. Although electric heating of suits to maintain the body temperature and improvement in construction of the suits to increase mobility and reduce the fatigue of maneuvering the diving rig have been effective in improving the performance of divers, the length of stay at the feasible work depths is still short. The resistance to movement and the difficulty of working against water movements is so telling on the strength of divers that effective work cannot be carried out for the recommended periods except under very favorable conditions of weather and currents.[42]

In caisson work the periods of work are longer in general, and as a rule the pressures encountered are limited by the nature of the operations. Pressure depths equivalent to about 100 feet probably are not often encountered and a work period of 1.5 hours twice a day has been used at such levels.[47] Since the conditions for performing useful work are in most cases better for caisson workers than for divers, some difference is understandable. On the other hand, the caisson worker is undoubtedly more nearly saturated than is the diver under these practices and thus more subject to sequelae if proper decompressions are not carried out. It has been the practice in this country for caisson crews to work in divided shifts.[42] The incidence of bends reported by Jones *et al.*[48] is 1.27 per thousand decompressions after a 1.5-hour shift but, because of the reluctance of workers to report mild cases or to have treatment on their own time, there is some question whether complete coverage was obtained. It was found that in tests of prophylaxis, where attention was directed to reporting all cases and where no stigma was attached to such reporting, the incidence was 2.05 per thousand despite the complete lack of any severe cases. Other groups showed incidences of 2.49 to 2.24 per thousand when no treatment or supervision by interested personnel was maintained. The latter higher incidence is undoubtedly related to the extremely casual manner in which decompression is carried out at the insistence of the men themselves.

2. Effects on the Circulation

In an academic sense, the blood can carry in physical solution enough oxygen to supply tissue respiration when the inspired partial pressure of oxygen is equivalent to 3 atm.,[16] whereas while breathing 1 atm. of air, less than 1 per cent of the oxygen carried by the blood is in physical solution. The full carrying capacity of the hemoglobin is attained, however, with only slight increase in alveolar pO_2. Therefore, it would seem that oxygen transport per se is more than adequate in compressed air atmospheres.

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[47] *Occupation and Health.* International Labour Office, Geneva, 1930.

[48] R. R. Jones, J. W. Grosson, F. E. Griffith, R. R. Sayers, H. H. Schrenk, and E. Levy, *J. Ind. Hyg. Toxicol.*, **22**, 427 (1940).

The situation with regard to CO_2 is by the same token not so favorable. This follows from the fact that the carbon dioxide from the tissues is less readily taken up by the hemoglobin under these conditions and a rise in venous pCO_2 occurs accompanied by a fall in pH with the attainment of the buffer capacity of the blood. Behnke *et al.*[49] showed that the change in pH at 4 atm. of oxygen amounted to 0.03 in the venous blood. As indicated above a further temporary enhancement of this effect may follow rapid compression.[30]

In general the pulse pressure and circulation are not uniformly changed by increase in atmospheric pressure, but when very high partial pressures of oxygen are obtained, complicating effects from the impaired carbon dioxide transport cause some changes. It is probable that dilation of cerebral and peripheral vessels is effected.[30]

3. Oxygen Poisoning

At from 3 to 4 atm. of oxygen, or corresponding oxygen pressure in air, certain motor disturbances of cerebrocortical origin develop. The syndrome is called "oxygen poisoning" and may show only minor twitches but usually progresses to full-blown convulsions within a short time. This is an acute condition related qualitatively to symptoms known to affect individuals maintained at a partial pressure of oxygen above about 600 mm. Hg for periods of several days.[50] The primary effects at normal atmospheric pressure seem to be a pulmonary involvement resulting in substernal distress and coughing with a clinical picture of lung congestion, while the acute conditions brought on by exposure to high partial pressures of oxygen over short intervals at increased atmospheric pressures affect the central nervous system, causing seizures, loss of consciousness, narrowing of the visual fields through scotomata, and so forth, which overshadow the appearance of less spectacular symptoms. The modus operandi of oxygen poisoning is in considerable dispute at the present time since both CO_2 and O_2 are known to have destructive effects on isolated systems at increased pressure.[30] Studies tend to show that irreversible or incompletely reversible changes take place in all intracellular reactions and particularly in the central nervous system, and there is good reason to believe that the normal gas-handling systems involving enzymes are intimately affected.[30] It has been shown recently that oxygen toxicity is not initiated by interference with the transport of carbon dioxide from tissues to lungs.[51]

4. Inert Gas Effects

From the experimental work on deep-sea diving and salvage it was reported by Behnke and Yarbrough[52] and Case and Haldane[36] that helium reduced the severity of a syndrome that attends exposure to high pressure atmospheres, about 10 atm., even though oxygen tensions were maintained at the normal level. This work resulted from an attempt to find a diluent for oxygen less soluble than nitrogen. According to Behnke and Yarbrough[52] argon and nitrogen have a narcotic effect at high atmospheric pressures that is proportional to the molecular weight and oil/water solubility ratio. Recently it has been shown that xenon, helium, and argon have definite effects in man and lower animals that are probably physicochemical in mechanism, but for which there is at present not even a hypothetical basis for action.[37,39] The correlation between the narcotic responses of the inert gases and their oil/water solubility ratios, as is true for narcotic substances generally, and the common property of a lack of active chemical effects lend substance to the claims of Behnke.

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[49] A. R. Behnke, L. A. Shaw, C. W. Shilling, R. M. Thompson, and A. C. Messer, *Am. J. Physiol.*, **107,** 13 (1934).

[50] H. Becker-Freyseng and H. G. Clamann, *Luftfahrtmedizin,* **7,** 272 (1942).

[51] Lambertsen *et al., J. Appl. Physiol.,* **6,** No. 6, 358 (1953).

5. Effects of Temperature and Humidity

At the pressures existing in most caisson installations the incidence of disturbances during maintained pressure is very low, but nevertheless after long exposures some prostrations have been reported. At the level of pressure existing in these instances there is no reason to expect "oxygen poisoning," and it has been impossible to show such effects in experimental work on animals in compressed air.[53] Disorientation, epileptiform seizures, and painful cramps of the arms and legs seem to be the most marked symptoms and are not readily differentiable from the syndrome appearing after decompression. There is thus some evidence that with complete saturation at even moderate pressures disturbances of central origin may be expected. It is possible that in actual practice other factors, such as heat and humidity, play a role not fully recognized because the attention of investigators is drawn by the hazards of compressed air as discussed elsewhere.

The effects of temperature during positive pressure work shifts are similar to those at normal atmospheric pressure except for qualitative differences brought about by the fact that humidity values are always high, and the normal modes of heat loss are thus restricted to radiation and convection. Temperatures of 90.0° F. are often encountered in caisson work because of the lack of heat exchangers between the compressors and the inlet ports to the caisson and the exposed situation of some equipment. In such an environment prostration due to excessive sweating and circulatory disorders are bound to occur. In the event that these reactions are subclinical but followed by uncritical decompression they may act as predisposing factors for the sequelae of bends and more severe responses. In all caisson work ventilation is effected in one way or another and there are minimum rates set up by local authority that are designed to prevent the accumulation of CO_2 respired by the workers.[42] In general this ventilation does not serve to lower the temperature of the caisson.

[53] A. R. Behnke and O. D. Yarbrough, *Am. J. Physiol.*, **126**, 409 (1939).

6. Other Effects and Subjective Responses

Subjectively, the attainment of positive pressure levels seems to result in an exhilaration or euphoria, which has been thought to be reflected in an increased capacity for muscular work,[53] but the effect soon gives way to a depressed state. Disturbances of the senses of smell and taste may appear. Alterations of the voice are a constant feature of speech in compressed-air atmospheres. The explanation for this phenomenon has not been established, despite attempts to show that density and its effects on the resonance chambers of the head and chest produce similar changes. The same changes and difficulties of speech, nasal high-pitched sounds, and straining of the muscles of the larynx, can be elicited at normal pressure when breathing oxygen mixtures containing hydrogen or helium, and no change back to the normal tone can be effected by increasing the absolute pressure of such mixtures. As far as can be ascertained these changes due to compressed air are strictly reversible except perhaps for the soreness of the laryngeal surfaces and muscles produced by straining.

C. DISCHARGE OF GASES FROM THE BODY FOLLOWING EXPOSURE TO INCREASED ATMOSPHERIC PRESSURE: DECOMPRESSION

1. Mechanical Effects

Discussion of the mechanical effects of decreasing the pressure of the gases surrounding the body may be arbitrarily limited to the condition that a discrete gas phase already be present, as in the middle ear, intestinal gases, etc. Although there is no question that gases freed from solution do exert a mechanical effect both extra- and intravascularly, the latter will be considered separately.

In the middle ear there is usually no serious effect unless complete closure of the eustachian tube has occurred. Since this condition would have precluded entrance to positive pressure, the incidence of middle ear troubles is low. The same applies to the effects on the sinuses, and even though some blockage may occur, the pains that develop are mainly from displacement of the tissues and ischemia of the mucous linings and are relatively minor. It is possible that movement of the round window separating middle and inner ear lumens may permit injection and hemorrhage of the capillaries in the inner ear. This eventuality has a more serious prognosis than similar trauma in the middle ear because it may result in the scarring of the receptor tissues of the cochlea and consequent deafness to various frequencies of sound.

Although the expansion of intestinal gases is a potential hazard in decompression, little mention of it is made in the literature. This is perhaps due to the fact that in caisson and diving work elimination of flatus is generally accomplished before the shift is over and also to the indoctrination of workers in dietary regimes that avoid gas-producing food. In any event the presence of intestinal gas during rapid decompression will cause discomfort only in proportion to the expansion ratio effected in the routine followed. Since in most cases this involves the Haldane or Bornstein stage method of decompressing to half the starting pressure,[14,53] the expansion will be some two times (greater by the effect of water vapor[10]) the volume at equilibrium. In most cases this is a moderate stimulus to the smooth muscles of the gastrointestinal tract and results in the expulsion of the gas.

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[53] H. Gerbis and R. Koenig, *Drucklufterkrankungen.* Thieme, Leipzig, 1939.

A more serious consequence of mechanical nature is the rupture of the lungs during even moderate decompressions because of the failure to keep the respiratory passages open.[54] This rupture occurs mainly in cases of submarine escape where a tendency to hold the breath is the natural result of apprehension and unfamiliarity with the unusual environment. The incidence in caisson workers and divers is undetermined, but the individual should be warned against breath holding during decompression.

2. Bubble Formation

The rate of removal of a gas from a fluid must keep pace with the tendency to desaturation resulting from a fall in total pressure if the formation of a free gas phase, i.e. bubbes, is to be prevented. The physiology of bubble formation may be best evaluated by a consideration of the mechanism based on the kinetic theory of gases. The molecules of a liquid may exist in the gaseous state, and while in the gaseous state they have a higher average energy content than their fellows in the liquid state. Presumably, then, the average energy of gas molecules dissolved in a liquid composed of other molecules becomes equal to the average energy of the liquid molecules. A bubble of gas will not form unless sufficient energy is applied to enough gas molecules in a restricted locus to result in displacement of the liquid molecules. The chances for the spontaneous localization of such energy quantities are very slight and it is generally assumed that minute gas or vapor spaces large enough to permit initiation of bubbles are always present at liquid-solid interfaces under natural circumstances.[55-57] These spaces have been termed "gas nuclei." (Harvey[58] has been instrumental in popularizing this term, but it is probably less confusing to call the spaces *bubble nuclei*.)

The data gathered from many experiments on degassing by Kuper,[55] Piccard,[56] Harvey *et al.*,[59] and Dean[57] indicate that a free-gas phase forms readily only if a space is present into which the gas may diffuse. Relatively enormous supersaturations are possible in the absence of such bubble nuclei. It is probable that under normal life conditions nuclei exist in profusion, specifically at such points as on substances active in the transfer of gases, such as hemoglobin and other respiratory pigments. The question of the ultimate locus of bubble formation is one that is being actively investigated at this time, and until definitive evidence is at hand no further analysis can profitably be made.

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[54] I. B. Polak and B. H. Adams, *U. S. Naval Med. Bull.*, **30**, 165 (1932).

[55] J. B. H. Kuper, *Rept., Aviation Medicine Unit, Ind. Hyg. Research Lab., Nat'l Inst. Health*, Bethesda, Md. (1942).

[56] J. Piccard, *Proc. Staff Meetings Mayo Clinic*, **16**, 700 (1941).

[57] R. B. Dean, *J. Applied Physics*, **15**, 446 (1944).

[58] E. N. Harvey, A. H. Whitely, W. D. McElroy, D. C. Pease, and D. K. Barnes, *J. Cellular Comp. Physiol.*, **24**, 23 (1944).

[59] E. N. Harvey, D. K. Barnes, W. D. McElroy, A. H. Whitely, D. C. Pease, and K. W. Cooper, *J. Cellular Comp. Physiol.*, **24**, 1 (1944).

From the work of Gersh[60] it is indicated that a gross correlation of the distribution of bubbles with that of fat tissues is found in decompressions from positive pressure. It seems that these loci by virtue of their relatively high gas content have at least the requisite condition for maintaining patent bubbles whether or not they offer the highest incidence of nuclei among the various tissues of the body. In point of time it is evident, however, from these data that bubbles in the vessels appear in greater number than bubbles in fat, at least in the early stages of this condition.

The evolution of gases from solution in the various tissues of the body on decompression gives rise to the main body of sequelae and forms the basis of the occupational disease of workers in compressed-air atmospheres. The essential facts are that on decompression the body fluids are supersaturated to a varying degree depending on the pressure attained and the time of exposure. If the supersaturation is great enough in the face of a continuous loss of the gas through circulation and respiration, then discrete gas phases will form, both intra- and extravascularly. These accumulations of gas then act to disturb the normal functions of the tissues in which they appear in proportion to their number and size. Thus, in the vascular system bubbles are found to form largely in the venous vessels and they are carried to the right heart and lungs where they accumulate and are responsible for the symptoms known as the "chokes."[61] This is a disability of varying degree, depending upon the extent to which the circulation of the lungs is interfered with. In general, it is considered a serious condition and recompression is instituted as quickly as possible. The appearance of bubbles in the blood is usually accompanied by appearance of bubbles in the various tissues, the fatty tissues being most subject to bubble formation.[62,63] While the cause of the symptoms of "bends" and other peripheral symptoms, such as pruritus, tingling sensations, and joint and tendon pain, is still a moot point, there is little doubt that the presence of the bubbles constitutes one of the most reasonable mechanisms for the development of local ischemia in the tissues, particularly in the skin. End[64] and Swindle[65] indicate that intravascular bubbles may be secondary to the embolism caused by the agglutination of red cells following exposure to compressed air, but confirmation of this effect is lacking. In many instances, however, nonsymptomatic accumulations of gas are found in large quantity, as for instance in the fascial layers beneath the skin and between the muscles. They produce a crepitation during manipulation. The question of whether intra- or extravascular bubbles are responsible for such occlusions is an academic point, but one from which future prophylactic measures will evolve.

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[60] I. Gersh, G. E. Hawkinson, and E. H. Jenney, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **V** (1944). Also in *J. Cellular Comp. Physiol.,* **26,** 63 (1945).

[61] I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **X** (1945). Also in *J. Cellular Comp. Physiol.,* **26,** 101 (1945).

[62] I. Gersh, G. E. Hawkinson, E. N. Rathbun, and A. R. Behnke, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **II** (1944). Also in *J. Cellular Comp. Physiol.,* **24,** 35 (1944).

[63] I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **IX** (1945). C. E. Wagner, *ibid., Rept.* No. **IV** (1944).

Given the general mechanism of occlusion or embolism the whole gamut of symptoms presented by decompression sickness can be seen to have a common cause. In particular, the effects of central nervous system disorganization and breakdown are directly traceable to the anoxia of motor centers and the integrating mechanism of the cortex and medulla. Thus the reported "monoplegia, paraplegia, Ménière's complex, apoplectic deafness, vertigo, aphasia, hemiplegia, etc." are all manifestations of this basic mechanism, throughout the nervous system. In fact, the cause of death in the majority of cases is rather to be attributed to a cerebral embolic accident than to general anoxia from cardiac failure or a toxic effect of the exposure on the tissues.[53,61]

The statistical distribution of symptoms of caisson disease indicates that peripheral effects predominate.[53] This may be related to the fact that peripheral reservoirs of fat unload their nitrogen slowly and therefore are subject to bubble formation, while only in case of gross supersaturation of the individual will chokes and central nervous system disturbances appear.

It is possible that the caliber of the vessels in the lungs and the brain play some part in this distribution, since it is generally estimated that the capillaries are larger here than in other tissues; thus only when large bubbles form either directly or by fusion from smaller bubbles will effects in these regions be expected.

3. *Rate of Decompression*

The problem of desaturating the tissues without causing bubble formation has been recognized since Bert's researches.[4] The first attempts to circumvent this phenomenon were not very successful and were extremely time-consuming because it was thought that uniform, slow decompression would prevent bubbles from being initiated. This procedure, however, resulted in maintaining such a low differential pressure across the interface between tissue and environment that transfer of gas was slow, and bubbles formed despite all precautions. Haldane[14] then instituted the technique of decompressing rapidly to such a pressure as to create a large differential pressure between tissues and environment but still small enough to prevent bubble formation in the time used for desaturation. After desaturating at this level for an appropriate period the pressure was again reduced and a somewhat longer period of desaturation followed. By extension this procedure will bring the diver to the surface in considerably less time than with the former method and without as great a hazard. It was shown experimentally that the pressure could be safely reduced to one half at each stage, and the period of desaturation was calculated from composite data on the different rates of desaturation of various tissues of the body.

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[64] E. End, *J. Ind. Hyg. Toxicol.*, **20**, 511 (1938).

[65] P. F. Swindle, *Am. J. Physiol.*, **120**, 59 (1937).

The method outlined above is essentially the one in use in all decompression procedures, but certain minor innovations have been applied by subsequent experimenters.[66] The Continental practice is a similar modification introduced by Bornstein,[53] in which the initial rapid reduction in pressure is made as in Haldane's method, but subsequently a continuous slow ascent is made. This method, according to its originator, maintains the gradient of pressure effected by the initial pressure drop throughout the decompression and further reduces the total decompression time.

The diving tables in use in this country are constructed on the stage basis of Haldane but include an ascent between stages of not more than 25 feet per minute.[46] Acceleration of the ascent schedule has been effected by the introduction of ventilative breathing of pure oxygen at the later stages when the total pressure is low enough to avoid effects of oxygen poisoning, but for economic reasons this method is used only in decompressions after recompression following bends or other serious decompression symptoms.[67] The use of helium in place of nitrogen has been advocated because of its lower solubility, but its principal contribution is the elimination of "nitrogen narcosis" in deep diving.[40,64,65,68]

The practice in decompression for caisson workers is a continuous slow reduction to one half the working pressure. Attempts to decrease the incidence of bends by oxygen breathing have been made with some success.[48] Uniform decompression rates have been prescribed by law[47] in the past, but changes in the codes have been made to take advantage of more rapid methods, with due consideration for safety. In many instances there is an over-all limitation in the minimum period for decompression without strict interpretation of the initial rate of pressure reduction. Because of marked fog formation in this practice, and the lowering of the decompression chamber temperature during this procedure, serious consideration is given in Continental codes[53] to moderate recompressions following each stage of decompression, in order to warm the air slightly and thus avoid chilling the men who have been at hard work in a hot and humid atmosphere. This practice is based on the fact that peripheral circulation is practically occluded by vasomotor response to lowering of the temperature, and thus desaturation of the skin and adjacent tissues is prevented, with the unpleasant results of bends, itching, and similar sequelae.

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[66] A. E. Boycott, G. C. C. Damant, and J. S. Haldane, *J. Hyg.*, **8,** 342 (1908).

[67] O. E. Van der Aue, W. A. White, Jr., R. Hayter, E. S. Brinton, R. J. Keller, and A. R. Behnke, *Experimental Diving Unit, Navy Yard (Washington, D. C.) and Naval Med. Research Center (Bethesda, Md.), Research Project X-443, Rept.* No. **I** (1945).

[68] A. R. Behnke, R. M. Thomson, E. P. Motley, *Am. J. Physiol.*, **112,** 554 (1935). E. End, *Am. J. Physiol.,* **120,** 712 (1937).

As suggested above, the desaturation procedures described here do not proceed without occasional symptoms of decompression sickness, and this debility may appear for some hours after decompression because of bubbles from improperly desaturated nitrogen reservoirs. The subsequent lodgment of such bubbles in a critical point of the circulation will bring about the same symptoms as mentioned above and in the same range of severity. Thus, it is necessary to keep decompressed individuals within reach of recompression equipment and to apply pressure and ventilative breathing of oxygen until remission of symptoms is complete.[67] The re-solution of bubbles is slow at recompression conditions because of the decreased bubble surface presented during recompression.[55] Unfortunately, these procedures often have been carried out on the worker's time, thus introducing a deterrent factor, and therefore many cases have been prolonged unnecessarily. In large part, the blame for poor decompression technique falls on the workers themselves, since they are often reckless in their haste to decompress and get off the job; and many have the ill-conceived notion that they have tough constitutions that will enable them to absorb such abrupt changes without permanent effects.[48]

Repeated exposure to bends symptoms, and perhaps even the mere repetition of decompression without discernible symptoms, will in time produce effects in those regions where bubble formation usually takes place.[53] In general, these chronic lesions are situated in the joints and in other tissues with poor circulation. They are thought to be the result of bubble trauma and repeated acute, or chronic, low-grade anoxia of the local tissues. They include: simulated arthritic effects of hip and knee joints; ankylosis of the incus, malleus, and stapes of the middle ear; thickening of the drum; and so forth.[53]

IV. Effects of Reduced Atmospheric Pressure on the Body

Ascent into the atmosphere simulates physically the conditions attending decompression from increased atmospheric pressures. It will be seen, however, that the ratio of pressure change permissible for the diver cannot be attained by the aviator. Thus, divers can work at 10 atm., a ninefold difference from their natural environment, yet at $^1/_2$ atm. there is serious disturbance for the aviator, and few, even hardened and acclimated, men have ever attained $^1/_3$ atm. for more than passing intervals.[6] The difference in range is mainly due to the fact that the decrease in barometric pressure on ascent to altitude strikes at the only component of the body's energy-liberating mechanism that it is unable to store to any reasonable extent: oxygen. The following sections will deal with this and other limiting factors in a manner comparable to that of the preceding section on positive pressures.

A. DISCHARGE OF GASES FROM THE BODY: DECOMPRESSION

As in decompression from positive pressures, the reduction in environmental pressure causes a differential pressure to exist between the gases dissolved in the body and the ambient atmosphere. In this case, however, the body is usually in complete equilibrium with the inert gases and thus will be supersaturated as soon as any ascent is begun. Obviously, the body will lose part of all the gases dissolved in it, even oxygen if the rate of ascent is abrupt enough, and this efflux of gases is regulated by the access that the various parts of the body have to the exterior. Thus, the fatty tissues and those with poor vascularization will maintain a high differential pressure as compared with others more favorably endowed.

1. Rate of Ascent

At the present writing, the physical possibilities of rates of ascent can hardly be overestimated. Given a suitable initial change of acceleration, the practical limitations for the newer type of aircraft are actually beyond the capacity of the body for coping with the changes in the environment; for example, the little defensive rocket-propelled "viper" developed by the Germans for use against Allied bombers made a practically vertical ascent to over 30,000 feet in somewhat less than two minutes, and it is probable that this is not the maximum that can be attained for piloted aircraft. In any case, this rate of ascent induces a pressure differential of nitrogen of about 368 mm. Hg in a matter of minutes, discounting for the moment the loss of nitrogen in this time from some of the tissues. Thus, as will be seen below, ascents can be made in such time intervals that the normal routes of gas transfer cannot handle the amount of gas that tends to be freed from solution.

Catchpole and Gersh[69] have shown that for rabbits the critical rate of ascent lies somewhere near 7000 to 8000 f.p.m., even though the animals are breathing oxygen during ascent. At 4500 f.p.m., survival at 45,000 feet for 30 minutes indicated that serious effects were not incurred at this rate. In human decompressions to altitude more conservative estimates must be made, first, because of the difference in size and vascularization as compared with those of small mammals and, second, because of factors other than bubble formation. In decompression for experimental purposes where bends are to be avoided it has been the practice to ascend at about 2000 and 3000 f.p.m. In indoctrination ascents for fliers, the rate of ascent has been set as high as 5000 f.p.m. In the latter case, bends do occur in some instances and this routine has been used to assist in selection of air crews. The experience of the Army Air Corps[70] shows that ascent at maximum feasible rates of climb, about 5000 f.p.m., at the time of this writing produces a bends syndrome only above 18,000 feet, and the severity is dependent on contributing factors of exercise, cold, length of stay, and so forth.

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[69] H. R. Catchpole and I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept. No.* **VI** (1945). Also in *J. Cellular Comp. Physiol.,* **27,** 15 (1946).

[70] *War Dept., Tech. Manual* 1–705 (1941).

Of more fundamental nature is the relation of rate of ascent to the absolute pressure levels attained during ascent. That is, the partial pressure of oxygen during ascent falls, and ultimately a point is reached at which the saturation of the hemoglobin of the blood can no longer be effected. This level is generally defined as about 10,000 feet, since the first disturbances to psychomotor responses become measurable at this level. Thus, the rate of ascent determines the point in time at which the individual arrives at the critical levels. In the case of rapid ascent cited earlier, advantage was taken of even the limited storage that the body can effect for oxygen, that is, the reserve time or asphyxiation time, in that the discharge of the pilot's duties needed to be effected over only a period of minutes, and for this interval his oxygen reserve could be made to suffice. It is doubtful that such close figuring will be resorted to in the future unless it becomes a matter of desperation.

In general, the influence of rate of ascent can be obviated by the simple procedure of breathing oxygen from a mask, beginning before ascent to remove body nitrogen,[71] and continuing during ascent to prevent desaturation of the hemoglobin of the blood. This expedient raises the critical level to about 40,000 feet, at which point the absolute pressure just suffices to maintain proper saturation of the hemoglobin of the blood. To obtain independence of these factors it is necessary to maintain a pressure differential between the individual and his altitude environment. Various methods have been devised, but pressurization of cabins in aircraft seems to be the most suitable one.[11]

2. Evolution of Gases from Solution in Body Tissues during Ascent

It has been shown empirically that although rate of ascent has some influence on the incidence of decompression sickness, there is a delay in the onset of symptoms that is inversely related to the altitude attained. This correlates with the fact that bubbles must have a period of growth, either by diffusion of gas or by coalescence, before they become effective. This delay is usually long enough so that no symptoms appear during ascent to altitudes below 45,000 feet. The reasons for this delay are not known precisely, but it is apparent that, whatever the cause of the initial delay, the failure of bends to appear in slow ascent with oxygen breathing is most probably due to the relatively good inert-gas elimination attained.

It is known from diving practice and experimental work[14] that decompression from two atmospheres absolute can be carried out without risk of bends by rapid decompression to one atmosphere under normal conditions, and this ratio of pressures was shown to preclude bubble formation at any feasible level of absolute pressure. Although recent work[72,73] indicates that abnormal conditions of activity may decrease the ratio markedly, extension of this rule to reduced pressures is justified empirically since reports of bends or chokes from decompression to reduced pressure have not been made below 26,000 feet, or about $^1/_3$ atm.[74,75] In justice to the facts it must be added that human exposures to reduced pressure at such levels were nearly always carried out with added oxygen, although there was in such instances an appreciable partial pressure of nitrogen in the respired air.[70] When animals are exposed to reduced pressure, bubbles are rarely found after exposure to pressure-altitude equivalents under 15,000 feet,[76] even with the most extreme conditions of muscular stress. On the other hand, in resting animals this critical level is equal to or above that found for man, depending to some extent on the body size of test animals. The physical reasons for the lack of bubble formation with saturations below a critical level are not well understood, but it can be shown that *in vitro* the lack of properly dimensioned bubble nuclei will prevent bubble formation until the differential pressure has reached a definite level,[59,77] and that at each new level of pressure a new crop of bubbles arises from nuclei that were ineffective at lower differential pressures. It is therefore inferred that the lack of suitable bubble nuclei in the body is one of the limiting factors that allow such high supersaturations to exist without symptoms of decompression sickness.

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[71] A. H. Whiteley, W. D. McElroy, G. H. Warren and E. N. Harvey, *J. Cellular Comp. Physiol.*, **24**, 257 (1944).

3. Mechanical Effects

The mechanical effects of decompression to altitude are identical with those obtaining on decompression from high-pressure atmospheres. In general there are minor symptoms only, and these arise from the pressure exerted by entrapped air when the atmospheric pressure falls. The pressure exerted internally in the middle ear usually falls off readily by displacement of the air through the eustachean tube, and a similar discharge from the sinus spaces takes place unless congestion from colds or other inflammations closes off the openings into the nasopharynx. With such closure, a fall in atmospheric pressure will allow the internal gases to displace the blood from the tissues lining the space, and this ischemia plus displacement of the yielding portions of the space will cause a

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[72] M. Harris, W. E. Berg, D. M. Whitaker, V. C. Twitty, *J. Gen. Physiol.*, **28**, 241 (1945).

[73] E. N. Harvey, W. D. McElroy, A. H. Whitely, G. H. Warren, and D. C. Pease, *J. Cellular Comp. Physiol.*, **24**, 117 (1944). W. D. McElroy, A. H. Whitely, G. H. Warren, and E. N. Harvey, *ibid.*, **24**, 133 (1944). W. D. McElroy, A. H. Whitely, K. W. Cooper, D. C. Pease, G. H. Warren, and E. N. Harvey, *ibid.*, **24**, 273 (1944).

[74] R. A. Kritzler, *War Med.*, **6**, 369 (1944).

[75] H. A. Smedal and E. B. Brown, *U. S. Naval Air Training Bases, Pensacola, Fla., Project X-609, Rept.* No. **I** (1945).

[76] M. Harris, W. E. Berg, D. M. Whitaker, V. C. Twitty, and L. R. Blinks, *J. Gen. Physiol.*, **28**, 225 (1945).

[77] W. E. Berg, M. Harris, D. M. Whitaker, and V. C. Twitty, *J. Gen. Physiol.*, **28**, 253 (1945).

varying degree of pain. The mechanics of the openings to these spaces lends itself so well to relief of internal pressure that only with the most serious cases will more than fleeting sensations be experienced.[78]

On the other hand, there is a more drastic effect to be expected from the expansion of the gases in the gastrointestinal tract. As in the case of decompression from high atmospheric pressures, there is expansion, but the effect caused by water vapor is considerably exaggerated. This is due to the fact that the vapor pressure of water is constant with the temperature of the body and, since it is an increasingly larger part of the total pressure, as ascent is made it causes an increasingly larger distension of the soft-walled gas pockets.[10] Thus, a decompression from 10 atm. to 1 causes a volume increase of water-saturated air from 1 to 10.59, or a gain of a little more than half a volume over the dry expansion; while a decompression from 1 atm. to $^1/_{10}$ would result in a wet volume increase of 24.6 times, or a gain of 14.6 volumes over the dry expansion. Even at $^1/_5$ atm., 38,500 feet, there is a volume increase of 6.66 times rather than the fivefold dry expansion from one atmosphere. These considerations form the basis of the observation that at moderate altitudes flatus expansion can be readily handled by the normally induced movements of the smooth muscle of the gastrointestinal tract, but at an altitude of 30,000 feet or above the tendency of the smooth muscle to give way to gradually increasing internal pressures results in meteorism with all its attendant symptoms.

Besides the excruciating pain caused by these effects there is in addition a restriction of the movement of the diaphragm and thus a respiratory embarrassment. In any case, the prophylaxis of avoiding gas-forming foods and the treatment of early symptoms by massage and movement of the abdomen are soon put into practice by the individual who has the misfortune to experience this distress. According to an extensive series of uniformly conducted indoctrination ascents for Army airmen, Swann and Rosenthal[79] reported an incidence of gas pains severe enough to cause descent of 0.59 per cent; of these, less than 15 per cent occurred during ascent to 30,000 feet; 73 per cent occurred after arrival at the working level of 38,000 feet.

The most critical conditions for mechanical effects from decompression arise in the situation in which explosive decompression from pressurized cabins occurs. Under these conditions a volume change theoretically as great as 2.3 times the original volume was experienced in laboratory tests in 0.008 second without detectable harm. It is probable that the displacement of lung gases proceeded as indicated but the expansion of intestinal gases, if any, was somewhat less due to the tone of the muscles. Cabin pressurization, for the reasons discussed above, is decreased at great altitudes because of the lack of a margin of safety in the rate of decompression.[11] Breath holding is an obvious hazard that, although it has not occurred in these tests, might result in pulmonary emphysema, as in the submarine escape conditions cited earlier.[54]

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[78] O. E. Reynolds, H. C. Hutchins, A. Y. Werner, and F. R. Philbrook, *U. S. Naval Med. Bull.*, **46**, 845 (1946).

[79] H. G. Swann and T. B. Rosenthal, *A Survey of the Incidence of Decompression Sickness with Reference to Some Constitutional and Environmental Variants.* AAF School of Aviation Med., Randolph Field, Texas, August 8, 1944.

B. THE EFFECTS OF MAINTAINED LOW ATMOSPHERIC PRESSURE

1. *Hypoxia*

It is evident from the previous treatment of the physical nature of reduction of barometric pressure that the partial pressure of oxygen falls in direct proportion to that of the total pressure. Thus an ascent to $^1/_2$ atm. pressure will result in an ambient partial pressure of oxygen equal to 79.5 mm. Hg. From Figure 4 it is seen that the theoretical saturation of the blood with oxygen might be as great as 95 per cent if this were the actual partial pressure of oxygen at the lung capillaries. Because gaseous exchange takes place within the depths of the lungs, and because there is never a complete exchange of the contained gases of the lungs, the partial pressure of oxygen is subject to several factors that bring about a reduction in its magnitude. The first is a matter of dilution with the residual gases in the lungs and their large air passages; the second is an addition of water vapor to the air from the moist surfaces of the lungs. The former is a structural factor that varies from one individual to another; the latter varies only with the temperature of the evaporating surface within the lung. It becomes apparent now that the water vapor is a sort of constant that we must arbitrarily deduct from the total barometric pressure in order to find the effective pressure and that, moreover, it becomes a larger and larger part of the total pressure as we ascend. At $^1/_2$ atm.,[11] by analysis, the composition of the gases nearest the circulating blood, the so-called alveolar gas, has an oxygen partial pressure of only 36 mm. Hg, which would result in a saturation of the arterial blood of less than 70 per cent. It is this reduction in the saturation of the blood that is the primary factor in the disturbances attendant upon ascent to high altitudes, since it interferes with the adequate transport of oxygen to the tissues, particularly those of the central nervous system that have the highest rate of metabolism and the smallest reserve.[6,11]

The reduction in partial pressure of the oxygen in the blood will excite the reflex mechanism of the carotid artery bulb, which excitation effects an increase in the rate of ventilation of the lungs, resulting in the removal of carbon dioxide (and perhaps some water vapor), with moderate improvement in the partial pressure of the oxygen in the lungs. While this response to lowered oxygen pressure in the blood is purposeful at normal atmospheric pressure, it is rarely called upon and less effective than a parallel mechanism of the respiratory center in the medulla. The latter responds to the increase in carbon dioxide that ordinarily follows oxygen depletion in the body from muscular exertion. This mechanism is, however, also responsive to a decrement in the partial pressure of carbon dioxide, and to the exclusion of excitations of the carotid bulb mechanism due to reduced oxygen pressures in the circulating blood. At altitude, therefore, a dilemma soon arises. Ventilation increases in response to the lowered oxygen pressure. This washes out carbon dioxide from the lungs and blood, with the result that ventilation falls off again. Thus a vicious cycle of fluctuating respiration sets in, with a progressive drop in oxygen pressure and saturation of the blood until central nervous system metabolism is so depressed that dysfunction and failure occur. Cyclic respiration has been described frequently as an early symptom of mountain sickness and is symptomatically equivalent to Cheyne-Stokes breathing. At intermediate altitudes, breathing air, and at equivalent altitudes, breathing oxygen, it is observed that equilibria in respiration may be attained by normal individuals in such a manner that effective ventilation for oxygenation may be maintained by the adjustment of CO_2 levels in the blood and accommodation of the respiratory centers to this altered milieu. A concise exposition of alveolar gases and ventilation phenomena has been formulated by Fenn, Rahn, and Otis[80] with numerous charts illustrating the effects of different levels of altitude. In practice this information may be applied industrially at high terrestrial altitudes, for example, in mining, but the use of pressurization and supplementary oxygen in commercial aviation makes it necessary for consideration only in emergencies.

While the acute response to oxygen lack may be unconsciousness and ultimate death, the more chronic exposure to low-grade hypoxia may produce a variable response ranging from inefficiency in both muscular control and mental processes to disturbances of central nervous system structures, inducing a neurocirculatory collapse, or at higher altitudes a peripheral circulatory collapse, which results in a state of shock with its attendant progressive deterioration.[6,11] It is probable that nearly all these derangements have a common mechanism rooted in nerve-tissue hypoxia,[81] but the variable responses that can be elicited from such a complex structure take on such a confusing aspect that analysis to a single cause is not practicable.[82]

2. *Hypocapnia*

As suggested above, the partial pressure of carbon dioxide undergoes changes at altitude as a secondary response to the hypoxia. Its effects are, nevertheless, quite marked and unfortunately unadapted to the circumstances. The loss of carbon dioxide from the blood can be seen from Figure 4 to cause more oxygen to be combined with hemoglobin at the same pressure of oxygen than before such a depletion. While this may at first seem to be satisfactory in increasing the

[80] W. O. Fenn, H. Rahn, and A. B. Otis, *Am. J. Physiol.,* **146,** 637 (1946).

[81] W. P. Yant, J. Chornyak, H. H. Schrenk, F. A. Patty, and R. R. Sayers, *U. S. Pub. Health Bull.* No. **211** (1934).

[82] G. A. Brown, C. L. Cronick, H. L. Motley, E. J. Kocur, and W. O. Klingman, *War Med.,* **7,** 157 (1945).

transport of oxygen, it will be effective in the tissues only if the carbon dioxide pressure is maintained or raised through increased metabolism. The hemoglobin will have a correspondingly increased affinity for oxygen in the capillaries if the pressure of carbon dioxide is decreased there as in the lungs. Unfortunately, the conditions that cause the hypoxia are not metabolic and thus carbon dioxide partial pressure falls throughout the body. This falling of the pressure brings on the depression in ventilation discussed above, and also a train of other effects characteristic of this condition.[11] Thus, hypocapnia brings on peripheral sensory disturbances described as a tingling, especially of the hands, apprehension and other subtle psychological changes which are precursors of a more drastic central nervous system response, often inducing strong autonomic stimulations resulting in vomiting. The latter is particularly hazardous in aviation because the presence of a mask will result in aspiration of the vomitus and complete asphyxia unless immediate aid is rendered.[6]

If the hypoxia caused by breathing ambient air at altitude is avoided by breathing oxygen, then normal carbon dioxide pressures will be maintained; but as higher altitudes are reached, the internal maintenance of carbon dioxide pressure through metabolic activity imposes a growing restriction that has been suggested previously; that is, the partial pressure of carbon dioxide tends to remain constant and thus becomes a larger and larger part of the total pressure and in effect prevents the entrance of sufficient oxygen into the lungs at critical levels.

3. Water Vapor of the Lungs

The considerations above of the physical effects of carbon dioxide in displacing oxygen at altitude are shared equally by water vapor that is constantly being evaporated from the lung surface. Traditionally, the assumption has been made that the gases in the lung are saturated with water vapor at body temperature, but on reflection it will be seen that the physics of this system cannot justify such a conclusion without modification, particularly at high rates of ventilation. The energy expended in evaporating water from the alveolar surface must produce a cyclic variation in temperature of the blood leaving the lung capillaries. It is also known that the saturation of the gases depends on the diffusion of water vapor throughout the space, and thus the ratio of surface to volume will influence the degree of saturation attained at any time. The facts of the case are better stated as saturation at the temperature of the alveolar, bronchial, and tracheal gases, with respect to the time of exposure to the evaporating surface. Experimentally it has been shown that the degree of saturation of the whole breath is considerably less than calculated on the assumption of saturation at body temperature,[83] but there is little reason to doubt that at the alveolar surface the saturation is practically that imposed by the local temperature.

[83] G. E. Burch, *Science,* **102,** 619 (1945). L. H. Marshall and H. Specht, *Am. J. Physiol.,* **156,** 299 (1949).

4. Critical Altitudes

Practically, the gases in contact with the alveolar surface are diluted by both water vapor and carbon dioxide in the ratio of their combined partial pressures to the total barometric pressure. It is found experimentally that an altitude of about 41,500 feet is critical for hypoxic symptoms when pure oxygen is being breathed.[11] When pure oxygen is being inhaled, if one assumes a carbon dioxide pressure of 40 mm. Hg and a water vapor pressure of 47 mm. Hg, the pressure of oxygen at 41,500 feet can be no greater than 45 mm. Hg, equivalent to a hemoglobin saturation of not more than 80 per cent. This condition is attained when breathing ambient air at a level not strictly definable unless assumptions concerning the ventilation rate and respiratory quotient are made, but it is usually found that the critical level for unacclimatized individuals is at about 15,000 to 16,000 feet.[11]

The altitudes at which perceptible impairment, that is, objectively demonstrable impairment, is effected under the two conditions given above vary with the tests used to demonstrate it. Thus, effects on night vision are found at very low levels and necessitate the use of oxygen from the ground up for night flying even though low-level flying is to be carried out.[11] This finding from military experience should be one of the first to be applied to civilian flight, especially in passenger transport where hazard to the pilot is carried over directly to large numbers of individuals. At 10,000 to 12,000 feet the ability to adapt the eyes to night vision and the ability of discrimination of objects is cut to about one half when breathing ambient air.[11] The addition of enough oxygen to raise the partial pressure to that at ground level will correct this deficiency. In general, the use of oxygen is to be recommended at 10,000 feet if operations are carried on for several hours. The exact time of onset of deficiency for different individuals varies a great deal and prophylaxis is based on the most conservative interval for safety: a margin of 6 hours at 10,000 to 12,000 feet, 2 hours at 12,000 to 15,000 feet, and none above 15,000 feet have been found to be compatible with reasonable safety in selected groups of men, as in the military services,[11] but more recently the use of oxygen on all flights above 10,000 feet has been ordered.[79] Considerable caution should be exercised in transferring these values to civilian flying, especially to pilots of private craft.

5. Decompression Sickness

In discussing the effects of ascent it was indicated that the onset of effects from inert gas due to the supersaturation caused by ascent to altitude was usually delayed. This necessitates the discussion of these effects as they appear during sustained low pressure. The similarity of this condition to that found after decompressing to 1 atm. from high pressures is great enough to enable the same general approach to be carried over directly.

Because the terminology of these effects has been rather uncritical in its origin from compressed-air experience, workers in low-pressure studies have developed more specific interpretations of the names for the phenomena which occur: thus, the development of intravascular bubbles is called "aeroembolism," while extravascular bubbles are relegated to the category of "bends," which comprises both phenomena in compressed-air terminology except for bubbles in the lungs, which in both cases are called "chokes." Reference is made to these terms only because they appear in the literature of both fields and often constitute the only detail of symptomatology. In view of the fact that the theory that gas bubbles are the cause of the pain and other sequelae to decompression is contested with some reason by investigators,[11,30,84] the term "aeroembolism" has also been subject to some criticism. It is admitted, however, that in the fulminating cases of decompression sickness bubbles are found both intra- and extravascularly, and they certainly play a large part in the derangement of the body mechanisms whether primary or secondary in point of time.[69,84-87] The fact that recompression brings immediate relief lends great weight to the bubble theory of decompression sickness, whether of extra- or intravascular caharcter.[11]

The appearance of bubbles in the vascular system has been shown to occur in animals at 45,000 feet with great regularity even in the presence of oxygen breathing throughout the ascent.[86] These observations indicate that the removal of inert gases from the body is not fast enough to prevent the formation of persistent free-gas phases and that once these bubbles are formed they continue to grow until they can be demonstrated as circulating or embolic entities and within the tissues. Attempts to demonstrate bubbles within cells, particularly those not containing fat inclusions, have been largely unsuccessful,[84,87] and even extravascular bubbles have not been observed in experimental animals after death at 45,000 feet,[86] despite the fact that rather large gas accumulations between muscle masses, under the skin, and near the joints have been demonstrated in human subjects.[84] Another disconcerting fact concerning the etiology of symptoms from decompression sickness is that bends pain can be reduced by the occlusion of arterial vessels leading to the region affected.[11] This is not compatible with the embolic theory or local ischemia unless the action involves the compression of vascular or other sensory nerves that are stimulated by the local effects of emboli within the vessels. The fact that as little as 50 mm. Hg pressure over the tissues proximal to the site of bends pain will relieve the symptom indicates that the precise mechanism is not yet explainable by the mechanisms carried over from compressed-air studies.[11]

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[84] E. N. Harvey, *Bull. New York Acad. Med.*, **21,** 505 (1945).

[85] H. R. Catchpole and I. Gersh, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **VII** (1945). Also in *J. Cellular Comp. Physiol.*, **27,** 27 (1946).

[86] I. Gersh and H. R. Catchpole, *Naval Med. Research Inst., Research Project X-284, Rept.* No. **VIII** (1945).

[87] D. M. Whitaker, L. R. Blinks, W. E. Berg, V. C. Twitty, and M. Harris, *J. Gen. Physiol.*, **28,** 213 (1945).

The time of onset of symptoms of decompression sickness is inversely related to the rate of ascent, as described previously,[69] and is further related to the product of altitude and duration of exposure at each altitude.[11] Thus, unless the precaution of thorough denitrogenation is taken before ascent, there is always the possibility of the formation of bubbles provided the altitude is great and the stay protracted. In view of these considerations it seems desirable to assume that bubble nuclei are always present or at least are being continuously formed in the various tissues of the body and that their chances of survival and growth are enhanced in proportion to the concentration of inert gases. The site of such activity may well be the loci at which the respiratory gases are handled normally by each tissue, thus accounting for the low incidence of patent bubbles in tissue cells, where gas exchange is diffuse, as compared with the high incidence in the blood, where the intensity of gas exchange is of a very high order.

Harvey's theory [84] that hydrostatic factors are basically responsible for the initiation of bubble nuclei is based on the observations that exercise and straining are accelerating factors in bubble formation and that the accompanying rise in carbon dioxide concentration is less effective. It is a well-documented fact that performance of muscular exercise is a predisposing factor for bends and is thus a variable in the determination of the time of onset of decompression sickness symptoms.[11,84,85,87]

The effect of temperature on the production of symptoms of decompression sickness has not been conclusively demonstrated at altitude,[11] but the fact that a predisposition to such symptoms in caisson workers subject to chilling can be shown[53] leads to the assumption of a conservative point of view. The maintenance of comfortable skin temperatures by electrical heating for the preservation of the highest degree of co-ordination in the performance of flight duties obviates, except in the case of accident, the need for consideration of the effects of cold on decompression sickness. The rationale of the effect of cold at altitude is based on the vasoconstricting action of cold in the skin, inducing an interference with the elimination of inert gases, and the production of shivering, which tends to exaggerate the effects of muscular tension over those normally found.

There are at least two other variables that have been found to correlate directly with the incidence of decompression sickness: age and linear density (i.e., pounds per unit height).[11] Similar relations have been determined for decompression from high-pressure atmospheres.[16,62] The manner in which age increases the incidence of symptoms is not clear except perhaps in that the circulatory resiliency of young individuals may minimize effects that would be reported as noticeable in older men. It would be more understandable if the differential were only in the severity of symptoms because the effects on the capillary vessels of older men would be expected to be more drastic. The factor of linear density is undoubtedly tied up with body fat and the accompanying difference in vascularization of the tissue. As shown by Gersh,[86] the fatty tissues are poorly ventilated because the effective ratio of capillary surface to tissue volume is low as compared with tissues such as muscle, which are known to be free of extravascular bubbles.

6. Acclimatization

The repeated or continuous exposure of individuals to high altitudes has been studied mainly in connection with mountaineering and in connection with a few industries such as the Andean sulfur mining in Chile.[88] The effects noted were exclusively concerned with the reduction of the partial pressure of oxygen, since under the prevailing altitude levels decompression effects would not appear. The adjustments accomplished by the body under prolonged hypoxia of mild degree are mainly in an increase in the number of red cells and their hemoglobin content, and in the tidal volume and rate of ventilation of the lungs, as well as changes in the circulatory efficiency: all directed to the more adequate transport of oxygen to the tissues.[11,34] Under high altitude conditions, that is, where great stress is placed on the organism even on an intermittent basis, the reactions invoked become less adaptive and in certain respects impose further stresses that may result in serious damage to the circulatory system, particularly the heart.[89] At intermediate levels some of these responses may attain, and recede from, a maximum even under continuing stimulation.[90] Ruff and Strughold laid great emphasis on these reactions and recommended the regular exposure of aviators to these conditions at mountain rest camps.[6] It is apparent, however, that the use of supplementary oxygen at the great heights attained by present aircraft largely does away with the desirability of such acclimatization. It would be of value at intermediate levels only for protracted sojourn, such as described above. These changes take place with the passage of time in normal individuals though not without the symptoms and temporary disabilities, cyclic breathing, nausea, syncope, etc., collectively known as mountain sickness.

C. CHARGING OF THE BODY WITH GAS IN DESCENT: RECOMPRESSION

1. Re-solution of Gases. Relief of Decompression Sickness

One of the most comforting aspects of exposure to decreased barometric pressure is the fact that most of the dangers involved in this condition can be readily eliminated by recompression to atmospheric pressure. The exceptions are cases where a shocklike condition has developed to the point of collapse or just short of it, and where the simple restitution of high partial pressure of oxygen will not correct the trauma to the peripheral vascular bed and the attendant hemoconcentration. Bends pain, chokes, and even serious central effects will respond rapidly to recompression if recompression is instituted early enough. The remission of symptoms usually occurs at intermediate altitudes and nearly always before reaching ground level. This procedure is not a cure until some time has elapsed, since reascent within a reasonably short time will bring almost immediate recurrence of symptoms at the same site.[11] The reason for this delay in recovery is the same as in diving and caisson recompression: that is, the re-solution of bubbles is slowed down in direct proportion to their loss of surface by compression.[55] For all practical purposes, recompression and not resaturation is the important factor in relief from decompression sickness per se, but elimination of the hypoxic effects depends upon resaturation of the blood with oxygen, which is of course rapidly effected.

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[88] D. B. Dill, *Life, Heat, and Altitude*. Harvard Univ. Press, Cambridge, Mass., 1938.
[89] P. D. Altland and B. Highman, *Am. J. Physiol.,* **167,** 261 (1951).
[90] L. H. Marshall and H. Specht, *Am. J. Physiol.,* **163,** No. 3 (1950).

2. Mechanical Effects of Recompression

The mechanical effects of recompression are as hazardous as under similar conditions in work at positive pressures. The patency of the eustachean openings and those of the several sinuses must be assured in order to prevent the injection of blood into the capillary bed of the mucosa lining the various cavities in question. As stated earlier,[29] the pressure necessary to rupture the capillary walls is quickly attained in descent, and damage ranging from petechial to massive hemorrhage has been observed regularly in individuals who have difficulty in clearing these passages.[6,11]

During descent from altitudes at which oxygen must be used there is incurred a condition that is called "delayed acute aero-otitis media." It results from the charging of the middle ear with a high percentage of oxygen that is subsequently lost by absorption into the blood. If the nitrogen influx is not maintained at a proper rate, and it seems usually not to be unless the eustachean passage is intermittently opened, then a negative pressure develops in the middle ear, sealing the eustachean opening and eventually causing a varying degree of pain and discomfort, especially in individuals who are asleep. Practical prophylaxis has been shown by Bowen[91] to consist in removing the oxygen mask at air-breathing levels during descent, and prior to this, if feasible, ventilating the ear and sinuses with air during a "stage" descent, while interspersing oxygen breathing during halts at each stage. When difficulties of this nature arise in indoctrination and altitude-chamber work a more radical procedure can be applied. In this instance descent is made with air from even the highest levels since the time for descent can be made so short that supplementary oxygen need not be used. The ability to open the eustachean tubes must be assured before such maneuvers are attempted, yet it is surprising that with such rapid descent individuals having some difficulty at ordinary rates of descent will find less difficulty, presumably because of the continuous flow of gas into the middle ear.

3. Rate of Recompression

The rate of descent that can be effected is limited mainly by the several unquantitative variables and idiosyncrasies of sinus and ear ventilation, as suggested above and as described for divers and caisson workers. Recompression from 30,000 feet and above has been effected in the space of a minute routinely in the course of experimental work[91] without any untoward effect. With these rates of descent the compressional inflow effects described by Bean[30] should be apparent subjectively as well as objectively, yet no mention is made in the literature of such effects on descent from high altitudes. In a preliminary trial, continuous gas analysis of respired air indicated temporary carbon dioxide retention during rapid descent with a corresponding excess for several minutes following descent. The respiratory rate also showed an increment in the period immediately following the descent.[92] The data from experiments and experience with free fall in parachuting[11] indicate that mechanical effects are the only restricting factors in rapid descent. It is, of course, necessary to take into account the absolute pressure as well as the rate of descent because of the interval in which respirable air must be available. This is a real difficulty in parachuting from great heights because even in free fall the rate of descent is slow enough so that hypoxia may develop when an individual is jumping from 40,000 feet. About $2^1/_2$ minutes elapse in free fall from this altitude, and an open chute descent would take $24^1/_2$ minutes. Free fall is the method of choice until at least half an atmosphere of pressure is attained, not only from the point of view of avoiding hypoxia but also because of the excessively low temperatures at these heights.[11]

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[91] W. J. Bowen, *U. S. Naval Med. Bull.*, **44**, 247 (1944).

V. Comparison of Effects of High and Low Atmospheric Pressure

In the introduction to this chapter it was pointed out that the effects of barometric changes differed qualitatively as well as quantitatively in the ranges of absolute pressure above and below standard atmospheric pressure. The similarities and differences have been noted in the several sections. In the following lines a brief statement is made of the similarities and differences of effects on the physiology of normal individuals. The clinical and pathological features must be largely inferred from their physiological basis, and further detail should be sought in the several competent reviews, both classical and current, that are cited in the references.

The mechanical effect of pressure change on the ear and sinuses is qualitatively similar for both low-pressure and high-pressure atmospheres. The principal effect occurs on increase of pressure when for some reason pressure equalization by passage of air into the lumens cannot be effected. The main result is displacement of blood from the body into the capillary system of the tissues lining these cavities, with hemorrhage into the lumen. In the case of the middle ear, bursting of the drum also may result. A fall in pressure is usually not attended by severe effects but may result in driving blood out of the tissues within the cavity and forcing the ear drum outward. The construction of the normal passages connecting these structures with the exterior is mechanically adapted to relieve internal pressure readily.

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[92] Unpublished work by the Aviation Medicine Unit, Ind. Hyg. Research Lab., Natl. Inst. Health, Bethesda, Md.

The mechanical effects of atmospheric pressure change on gases enclosed within soft-walled structures, such as the gastrointestinal tract, are quantitatively different in the two ranges of pressure, in that the partial pressure of water enhances the volume change on decrease in pressure in inverse proportion to the absolute pressure. On increase of pressure there is no deleterious effect.

The effects of the partial pressure of oxygen with change in atmospheric pressure are qualitatively different in the two ranges of abnormal pressure. At increased pressures there is a tendency for "oxygen poisoning" to increase in proportion to the absolute pressure above a relatively low limiting value. At decreased atmospheric pressure there is, conversely, a progressive asphyxiation due to interference with the oxygen transport to the tissues and finally with the pressure-labile oxidative processes in the tissues.

The effects of the partial-pressure changes of inert gases are qualitatively similar in the two ranges of atmospheric pressure, in that reduction of pressure leads to supersaturation of the dissolved gases, with the consequent danger of the formation of bubbles within and without the vascular system. The causal relation between bubbles and the symptoms of decompression sickness is not wholly established, but the immediate relief of symptoms by recompression indicates a real relationship.

At high atmospheric pressures there is observed an additional effect on the central nervous system that has been attributed to the inert gases. A causal relation of carbon dioxide to it has been suggested in view of the lack of chemical activity of the inert gases, but neither approach can fully account for the observed effects. At low atmospheric pressures the biologically active gases produce such marked effects that no observations on the part played by inert gases, except as passive diluters of the oxygen, have been made.

At present, there are three extensive bibliographies of the literature in this field.[42,93,94] It is hoped that the references given here to reports of restricted circulation will aid the reader as an indication of the existence of the work and a subsequent search of the abstracting journals may reveal the ultimate place of publication.

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[93] E. C. Hoff and J. F. Fulton, *A Bibliography of Aviation Medicine*. Thomas, Springfield, Ill., 1942, p. 237.

[94] E. C. Hoff and L. J. Greenbaum, Jr., *A Bibliographical Sourcebook of Compressed Air Diving and Submarine Medicine*, Vol. II. NAVMED-P-5033. Office of Naval Research and Bureau of Medicine and Surgery, Department of the Navy, Washington, D. C., November, 1954

CHAPTER XVIII

Industrial Noise and the Conservation of Hearing*

JEROME R. COX, Jr.

Probably the best-known case of occupational loss of hearing is that of Quasimodo, the hunchback bellringer of Notre Dame. The events of this famous Victor Hugo novel took place in France in the year 1482. Centuries later during the industrial revolution medical science took note of the problem by coining the term "boilermaker's deafness." Only during the past few years, however, has society as a whole become aware of the harmful effects of extended exposure to intense noise. The recent widespread interest in the problem results from a combination of several factors.

The continued increase in the number of workers exposed to intense noise is surely a most important factor. From the time man first began to work metal he has produced sounds different from those of his natural environment. As civilization has developed man has found more and more ways of having machines do his work and each new machine added to his exposure to noise. Since industrial development was quite gradual, the increase in noise was gradual and has, until recently, been endured by all concerned without much protest. So great is the number of people now affected and so intense are some of the new noise sources, that industry can no longer afford to overlook the problem.

Coupled with this increased number of severe noise exposures is a general transfer of the responsibility for an occupational disability from the worker to the employer. With the passage of modern workmen's compensation laws this transfer has been accomplished for most traumatic injuries and occupational diseases. The burden of the responsibility for occupational hearing impairment is now shifting and eventually will surely be placed entirely on industry.

This shift in responsibility would be impractical without certain technological advances in the fields of acoustics and audiometry. The electronic audiometer has made reliable and repeatable hearing measurements possible in clinical circumstances. Improvements in noise-measuring equipment, at last, make it feasible to express a man's noise exposure quantitatively; and the tremendous strides made recently in the field of noise reduction promise a satisfactory solution to the problem through engineering control.

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* All illustrations not otherwise credited are furnished through the courtesy of the Liberty Mutual Life Insurance Company, where the author was employed during the preparation of a large part of the manuscript.

It is thus incumbent on industrial managements to recognize the trend toward more noisy occupations and toward compensation for industrial hearing loss; to understand the medical, legal, and engineering developments relative to industrial noise; and to examine their own operations in the light of these developments.

I. Fundamentals of Noise

Noise is frequently defined as any unwanted sound. This, however, is a functional definition and not a physical one. The question of whether a sound is wanted or not depends not only on the individual, but also on the circumstances. Let us momentarily bypass the subjective portion of the problem and examine the physical nature of sound.

A. WHAT IS SOUND?

Sound is a traveling disturbance, which usually appears as variations in the pressure and density of the atmosphere. A source of sound that is familiar yet physically simple is the tuning fork. When struck, the tines vibrate to and fro, setting the surrounding air into motion. The relative motion of the air in neighboring regions causes pressure fluctuations above and below atmospheric pressure. These pressure fluctuations, known as *compressions* (regions of increased pressure) and *rarefactions* (regions of reduced pressure), travel outward from the source in all directions and produce a *sound wave* (see Figure 1).

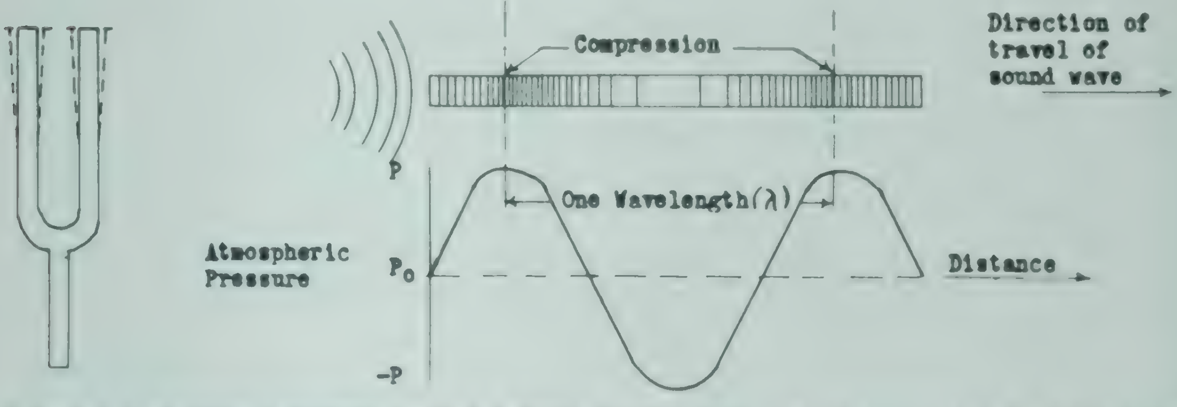

Figure 1. A schematic representation of a sound wave generated by a tuning fork and a plot of the sound pressure against distance at one instant of time. (After Pietrasanta.[1])

B. PURE TONES

The sound produced by a tuning fork is a simple tone, pure and steady. In fact, it is often called a pure tone. The pressure variations for such a tone follow the sine wave pattern shown in Figure 1. This figure shows the pressure pattern at a certain instant. Since the entire sound wave is travelling away from the source at a speed of about 1100 feet per second (the velocity of sound at freezing (32° F.) is 1087 feet per second, and it increases about one foot per second for each degree Fahrenheit increase in temperature), the pressure pattern an instant later would show the sine wave displaced slightly to the right.

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[1] A. C. Pietrasanta, Some fundamental principles of noise control. *Refrig. Eng.*, **62**, 37, 100 (April, 1954); **62**, 56, 96, 98, 102 (May, 1954).

C. FREQUENCY

Were the tuning fork smaller, the vibrations would be more rapid. More cycles, complete to and fro vibrations of the tines, would occur in a second. The frequency of the sound, which is the number of cycles per second (c.p.s.), would, therefore, be higher.

D. WAVE LENGTH

By the time this higher frequency sound wave has advanced the same distance as the one shown in Figure 1, more cycles of compression and rarefaction of the atmosphere would have been emitted by the source. In order that this increased number of cycles exist in the same space, the distance from the peak of one compression to the peak of the next must be smaller. This distance between compressions is called a wave length and is designated by the symbol λ (lambda). Its relationship to the frequency, f, and the speed of sound, c, is given by the equation:

$$f\lambda = c \tag{1}$$

For instance, for a frequency of 1100 c.p.s. the wave length is one foot; 110 c.p.s. the wave length would be 10 feet. In both cases the frequency times the wave length is equal to the speed of sound, and this relationship holds no matter what the frequency.

E. SOUND PRESSURE

It is easy to see that these two related quantities, frequency and wave length, do not describe completely the tone produced by the tuning fork. The fork may be hit lightly and produce a faint sound, or firmly and produce a loud sound. Both sounds will have exactly the same frequency and wave length since the tines will vibrate to and fro the same number of times in a second. The harder the fork is struck, however, the greater the distance the tines travel during each cycle. This increased distance travelled by the tines will cause greater pressure fluctuations above and below atmospheric pressure. Thus the harder the tines are struck, the greater the height of the sound wave shown in Figure 1.

The difference between the atmospheric pressure and the actual pressure during a rarefaction or compression resulting from a sound wave is called the *sound pressure*. A convenient way to measure this sound pressure is in fractions of a bar, which is a unit of pressure equal to atmospheric pressure (bar comes from the same Greek word as does the word barometer, the instrument that measures atmospheric pressure). The fluctuations in pressure that cause sound are extremely small compared to a bar (a pressure of about 15 pounds per square inch) and, therefore, it is convenient to use a much smaller unit, the microbar. This unit, sometimes abbreviated μbar, is equal to one millionth of a bar.

Thus the pure tone of Figure 1 is described completely by the frequency in cycles per second and the sound pressure in microbars. There is no relationship between the frequency and the pressure since a pure tone at a given frequency may have any sound pressure, large or small. Therefore, both frequency and sound pressure, or some two equivalent quantities, must always be reported in order to specify a sound completely.

F. SOUND POWER

Power is the rate at which energy is consumed or transmitted from place to place. For instance, in more familiar mechanical terms, a weight of one pound lifted one foot off the ground requires the expenditure of one foot-pound of energy. If it took just one second to lift the weight, the power involved would be one foot-pound per second. A rather small motor could be used to perform this task since there are 550 foot-pounds per second in one horsepower. Another familiar unit of power is the watt. It is equivalent to about three quarters of the foot-pound per second. The watt is familiar because it is the unit of power consumption of electrical apparatus. The watt is much smaller than the horsepower (there are 746 watts in a horsepower), and it is the unit most convenient for the measurement of sound power.

Sound power is an excellent measure of the sound-producing abilities of a source. Since the sound pressure generated by a source depends upon the location of the observer, it is much less ambiguous to specify the total sound power radiated by a source than to attempt to describe it in terms of sound pressure. The total sound power radiated by some familiar sources is shown in Table 1. This table makes use of certain prefixes, such as "micro," which means "one millionth of." Since the range of sound power produced by common sources is so tremendously broad it is necessary to use certain shorthand notations to eliminate the difficulty of writing many, many zeros. Instead of the prefix abbreviation one can use the exponential notation. Here the exponent indicates the number of places that the decimal point in the number 1.0 must be moved. When the exponent is positive, the decimal point is moved to the right; when negative, to the left. For instance, 10^2 is equivalent to 1.0 with the decimal point moved 2 places to the right, 100.

G. SOUND INTENSITY

The sound power per unit area is called the sound intensity. Thus, if sound power is distributed over an area in such a way that 1 watt of power falls on each square foot of the area, the sound intensity is 1 watt per square foot. Sound in-

TABLE 1

Approximate Power Radiated by Some Familiar Sound Sources

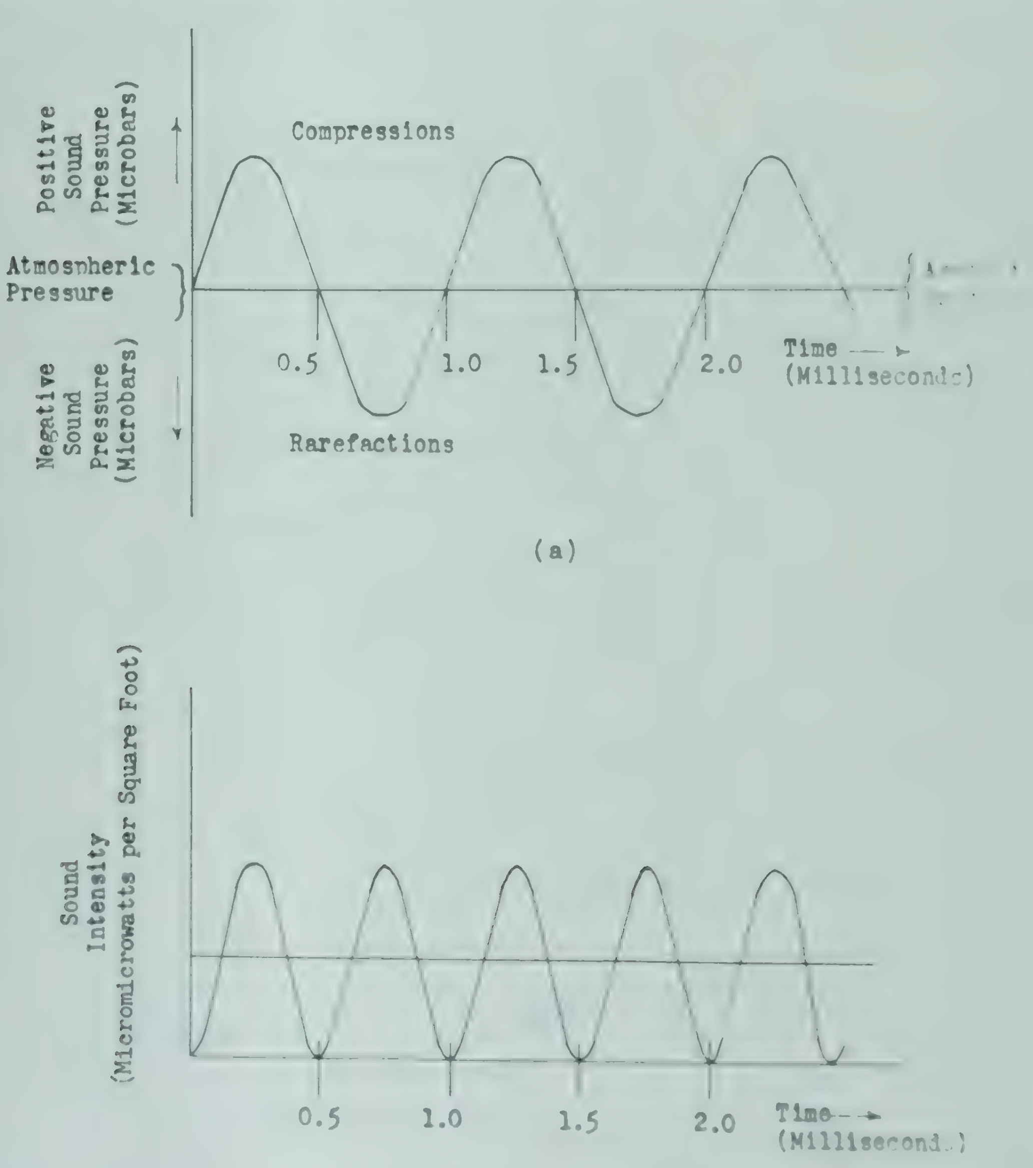
Watts	Prefix notation	Exponential notation	Sound source
10,000,000.	10 megawatts	10^{7}	
1,000,000.	1 megawatt	10^{6}	
100,000.	100 kilowatts	10^{5}	Future turbo-jet engine (est.)
10,000.	10 kilowatts	10^{4}	Turbo-jet engine, afterburner Turbo-jet engine, take-off
1,000.	1 kilowatt	10^{3}	2-engine airliner, take-off
100.	100 watts	10^{2}	Large wood planer
10.	10 watts	10^{1}	2-engine airliner, cruising Chipping hammer, large castings
1.	1 watt	10^{0}	
0.1	100 milliwatts	10^{-1}	Chipping hammer, small castings Circular saw, ripping plank
0.01	10 milliwatts	10^{-2}	Voice, shouting
0.001	1 milliwatt	10^{-3}	Auto on highway
0.000,1	100 microwatts	10^{-4}	Typewriter
0.000,01	10 microwatts	10^{-5}	Voice, conversational level
0.000,001	1 microwatt	10^{-6}	
0.000,000,1	100 millimicrowatts	10^{-7}	Telephone dial
0.000,000,01	10 millimicrowatts	10^{-8}	Voice, whisper
0.000,000,001	1 millimicrowatt	10^{-9}	Pencil writing on paper
0.000,000,000,1	100 micromicrowatts	10^{-10}	
0.000,000,000,01	10 micromicrowatts	10^{-11}	
0.000,000,000,001	1 micromicrowatt	10^{-12}	Normal breathing
0.000,000,000,000,1	0.1 micromicrowatt	10^{-13}	Man's wrist watch

tensity is an indication of the concentration of the sound power. When a certain sound power is distributed over a large area, the sound intensity will be much smaller than when the same power is concentrated in a small area.

It is often possible to compute the sound intensity from the sound pressure by using the equation:

$$I = (1.52\ p)^2 \tag{2}$$

where I is the sound intensity in μwatts per square foot, p the sound pressure in μbars, and the constant 1.52 holds for normal atmospheric conditions. Very close to a sound source and in regions where the reflection of sound from other surfaces is important this equation will not be correct. However, in the intermediate region between these two extremes it will be at least approximately right.



(a)

(b)

Figure 2. (*a*) Variations in *sound pressure* measured at a fixed point resulting from the passing of a 1000 c.p.s. wave. (*b*) Variations in *sound intensity* measured at a fixed point resulting from the passing of a 1000 c.p.s. wave.

As an example let us compute the sound intensity that is equivalent to the faintest sound discernible by a listener with acute hearing. Usually this listener can just barely hear a 1000 c.p.s. tone when the maximum pressure increase above and decrease below atmospheric pressure is about 0.00028 μbar (see Figure 2). Inserting this pressure in the equation gives a maximum sound intensity of 0.181 μμwatt per square foot (μμwatt is an abbreviation for micromicrowatt).

Notice in Figure 2 that the sound intensity is not steady, but varies in a pulsating fashion. With each rarefaction or compression a pulse of sound energy is carried away from the sound source. The average intensity is one half the maximum intensity. For more complicated sounds the average intensity is usually a great deal more meaningful than is the maximum intensity.

H. THE R.M.S. SOUND PRESSURE

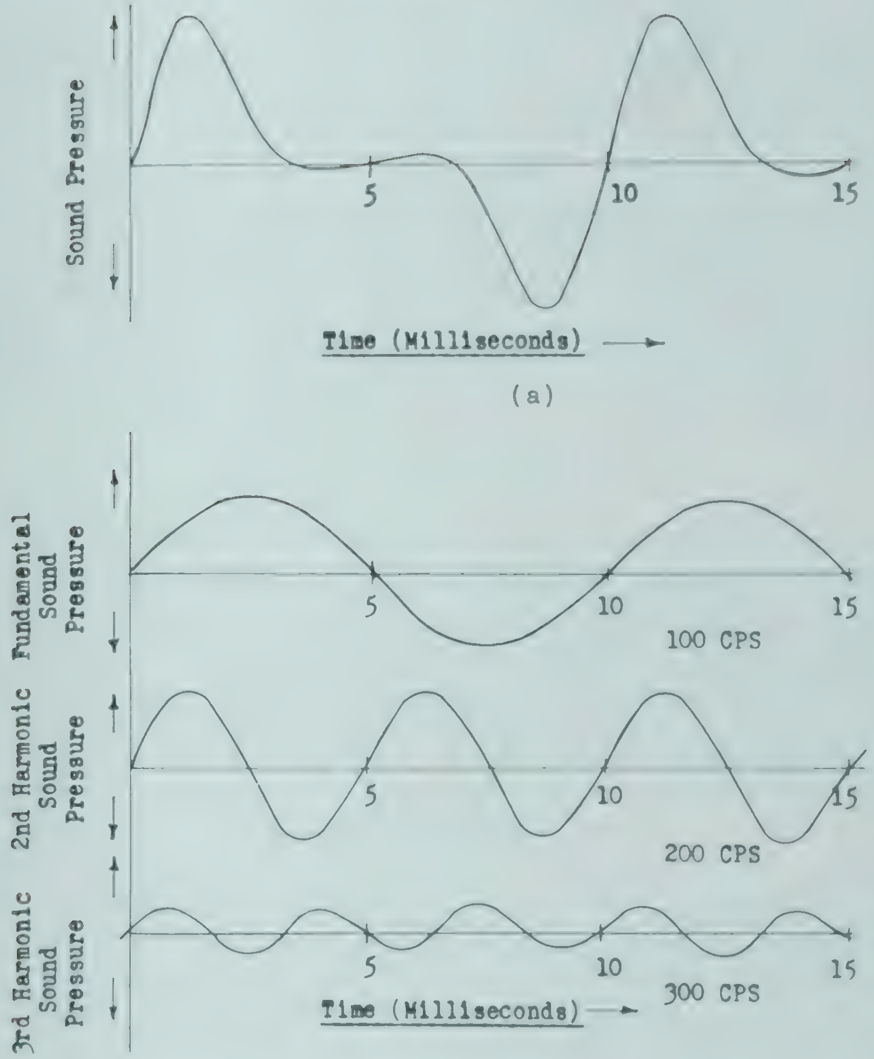
Sound-measuring instruments are designed to measure the r.m.s. sound pressure as closely as possible. The abbreviation r.m.s. stands for root-mean-square, which means that the sound pressures are first squared, then averaged, and finally the square root of the average is taken (the words "average" and "mean" are synonymous). In the example worked out above the barely audible 1000 c.p.s. tone had a maximum sound pressure of 0.00028 μbar. The equivalent r.m.s. sound pressure is 0.0002 μbar.

I. COMPLEX SOUNDS

Sounds measured by these instruments are rarely as simple as that produced by the tuning fork (Figures 1 and 2). Even the note of a violin is more complicated than the pure tone, for it is made up of a number of pure tones whose frequencies are related by simple numbers. As an example, consider the musical note in Figure 3a. It may be formed by adding together the three pure tones shown in Figure 3b. Any change in the sound pressure or frequency of these components would alter the resulting sound.

A pure tone sounded at the frequency of the lowest component, in this case 100 c.p.s., would have the same pitch as the combination of tones. However, the combination will be a richer, more musical sound than the single tone. This 100 c.p.s. tone is called the fundamental. The 200 and 300 c.p.s. tones are called the second and third harmonics, respectively. The number of the harmonic can always be computed by finding the number of times the frequency of the fundamental may be divided into the frequency of the harmonic. If the frequency of one sound cannot be related simply to the frequency of another, the combination of the two will be discordant. We then say that the sounds are inharmonically related.

Notice that the peak pressure variation caused by the combination of tones (Figure 3a) is only slightly greater than the peak pressure variations caused by the fundamental alone (Figure 3b). However, if we express the sound wave in



(a)

(b)

Figure 3. (*a*) Variations in sound pressure caused by a complex sound wave; (*b*) three pure-tone components of the sound wave shown in (*a*).

terms of sound intensity (Figure 4a), the sum of the average intensities of the components is equal to the average intensity of the combination.

J. FREQUENCY ANALYSIS

The complex sounds discussed in the foregoing paragraphs have been pictured by plotting the sound pressure as time passes (Figure 3a) (or sound intensity (Figure 4a)). From such a plot it is impossible to determine directly the frequencies of all the component tones. An analysis of a complex sound, such as that shown in Figure 3b, is necessary before the harmonics can be individually identified.

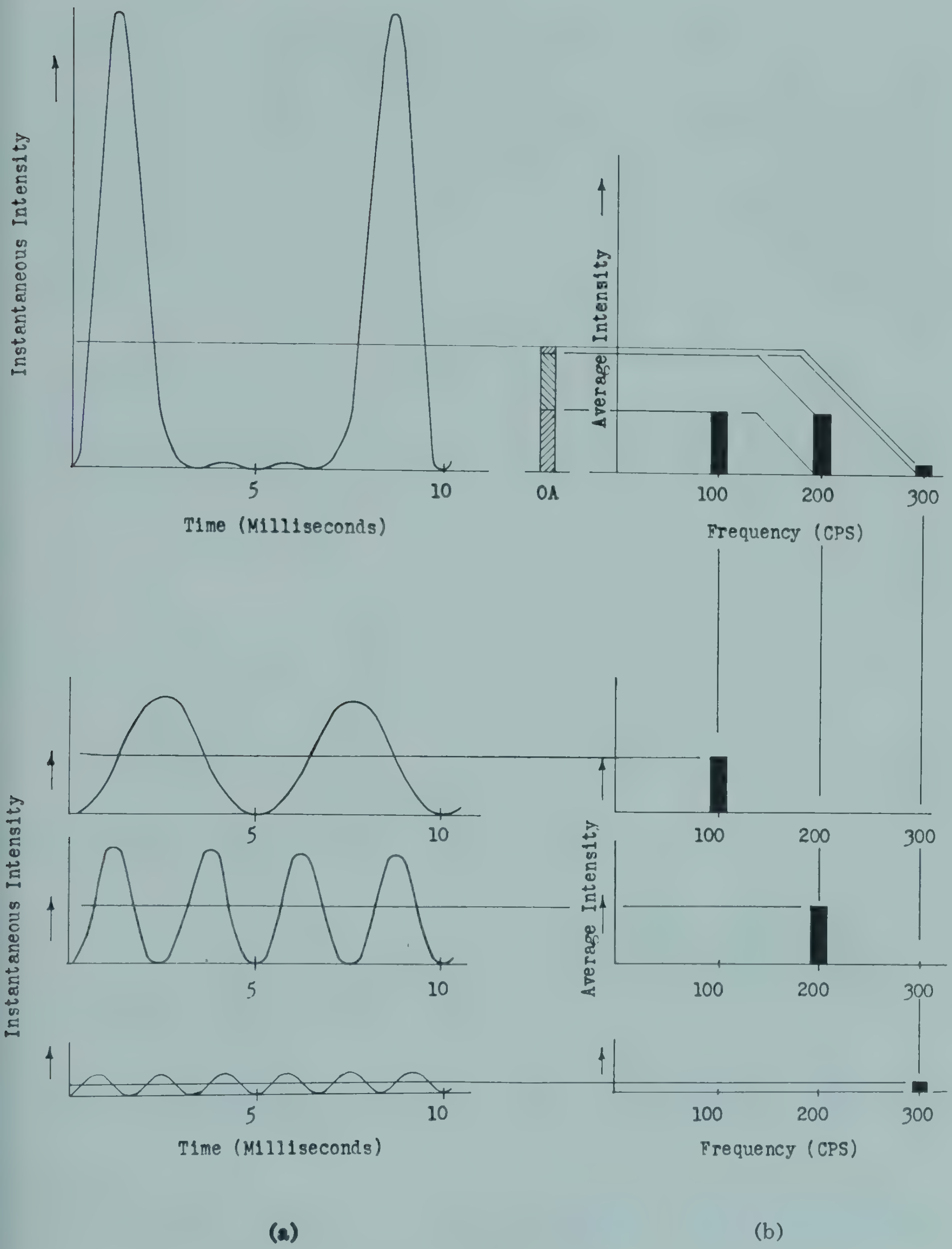


Figure 4. (*a*) The intensity of a complex sound and its components plotted against time; (*b*) the frequency representation of the same complex sound.

In many situations it is more important to know the frequency of the components of a sound than to know the exact behavior as time passes. Therefore, an alternative method of describing sounds called frequency analysis is often useful. For instance, in Figure 4b sound intensity has been plotted against frequency instead of against time as was the case in Figure 4a. Thus for the sound under consideration the three component frequencies are represented by three dark bars located at 100, 200, and 300 c.p.s. The heights of these bars are equal to the average intensities of the individual components. The sum of the three components equals the average intensity of the combination, shown by the cross-hatched bar in the center of Figure 4. The cross-hatched bar is labeled, OA, an abbreviation for the *over-all* (or total) value of the average sound intensity.

Nonmusical sounds, such as speech and noise, are usually made up of a vast number of frequency components, which, unlike the three tones in Figures 3 and 4, are not necessarily harmonically related to each other. This difference is demonstrated by a comparison of both time and frequency representations of three sounds, a pure tone, a complex sound, and a random noise (Figure 5). The comparison is plotted in terms of sound intensity as before. The r.m.s. sound pressure can be calculated from the intensity, however, by working backward in equation 2

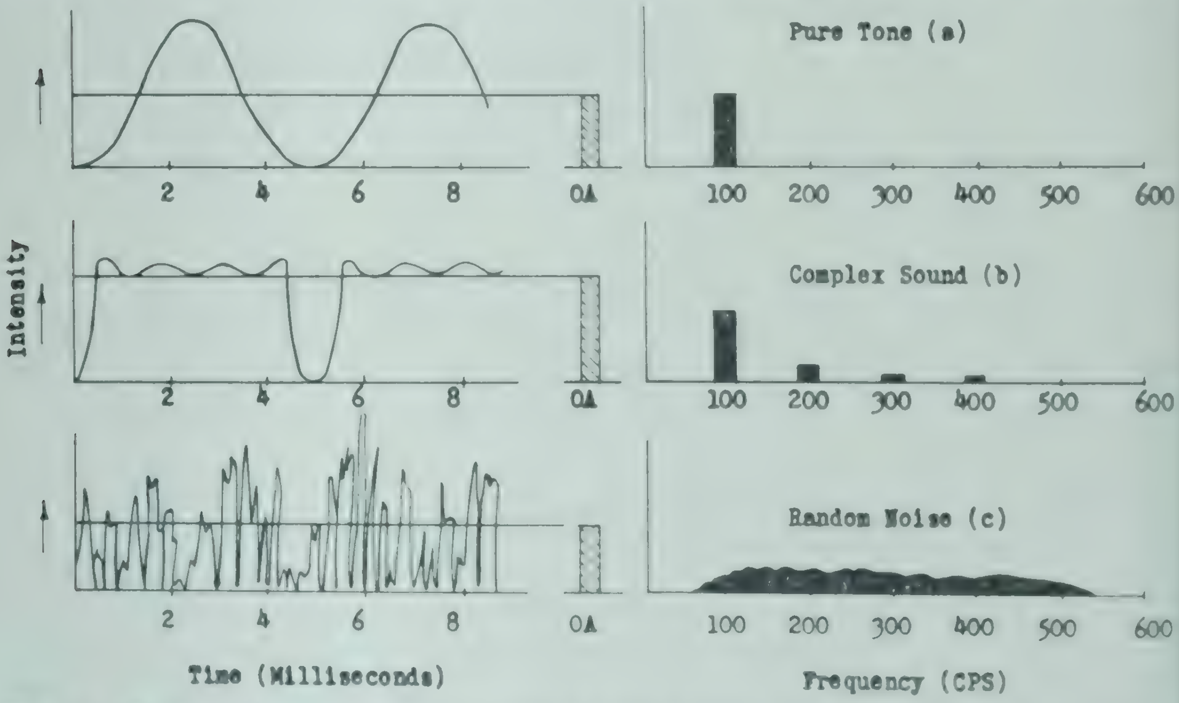


Figure 5. Time and frequency representations of three sounds: (a) a pure tone, (b) a complex tone, and (c) a random noise.

K. FREQUENCY BANDS

Since many of the sounds encountered in practice are at least as complicated as the one shown in Figure 5c, it is clearly an impossible task to measure the intensity of every component. A much easier scheme is to measure the total sound intensity in each of a set of frequency bands. Figure 6 shows three methods of dividing the audible frequency range into a complete set of frequency bands. Dividing the range into eight segments produces octave bands. The word octave is used here because it means that the upper limit of the frequency band is just twice the lower limit. The two remaining divisions of the frequency range utilize half-octave and third-octave bands.

In Figure 4b the over-all or total intensity was equal to the sum of the intensities of all the individual components. Likewise the sound intensity in any frequency band is equal to the sum of the intensities of the components within the frequency limits of that band. By the same rule the over-all intensity must be equal to the sum of the intensities in each of the frequency bands.

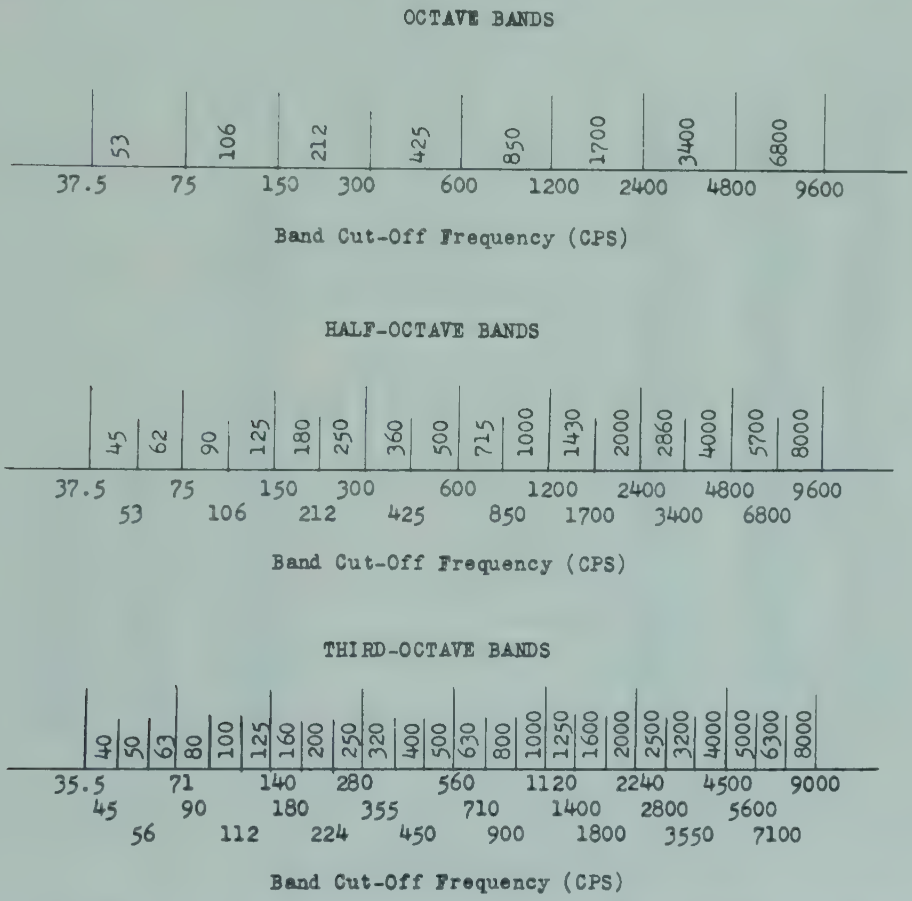


Figure 6. Three methods of dividing the audible frequency range into bands. The frequencies shown within the vertical lines are the mid-frequencies of the bands (geometric mean frequencies).

An example of the application of this rule and a method for recording actual measurements are shown in Figure 7a. This example reports the ambient sound intensity in a room for the testing of hearing. The vertical axis gives the intensity of the noise in μwatts per square foot. The horizontal axis gives the frequency limits of the band in which the intensity is measured. The first and last bands are not exact octaves for reasons of convenience. Note that the measurements in all but the lowest frequency band are too small to plot accurately. The noise in the higher octave bands is very important, however, in the evaluation of whether the room is quiet enough for hearing tests. Therefore, the intensity method of presenting the data is inadequate because it overemphasizes large components of sound and makes others almost too small to notice.

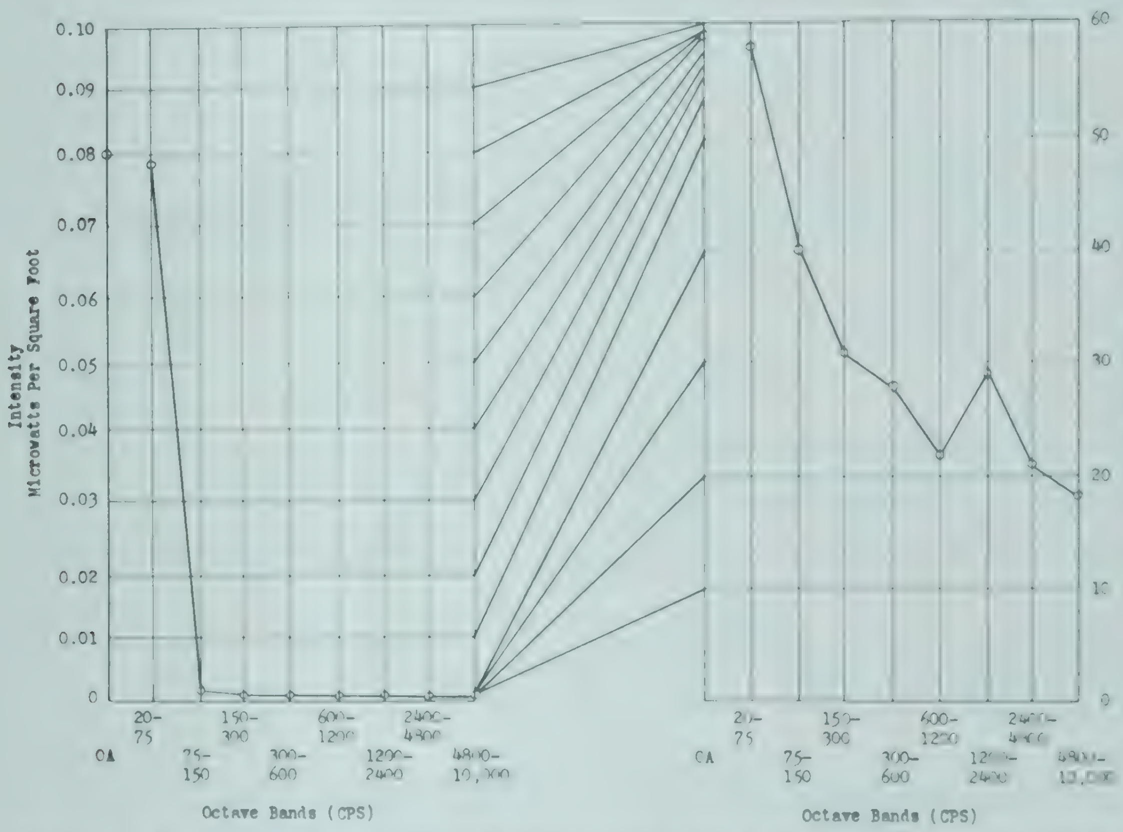


Figure 7. Two methods of recording the background noise in a room for audiometric testing

L. THE DECIBEL

What is needed is a scheme that expands the very small intensity range and contracts the large intensity range. A logarithmic or decibel (db) scale does this as is indicated by the sloping lines joining equivalent points on the two scales in Figure 7. The exact equivalence between sound intensity level in decibels and sound intensity is shown in Table 2. Note that 10 decibels is equal to a 10-fold change in the intensity; 20 decibels, to a 100-fold change; and 30 decibels, to a 1000-fold change.

The decibel scale allows a more meaningful presentation of the octave band measurements (Figure 7b). A peak in the octave band analysis in the 1200–2400 c.p.s. band is now evident, whereas the intensity method of presentation hides this information.

This example shows clearly an advantage of the decibel system. It also calls attention to one of the disadvantages. The sum of the octave band levels does not equal the over-all level. In the intensity presentation, it is possible to arrive at the over-all intensity merely by finding the sum of the intensities in the individual octave bands.

A more clear-cut example of this difficulty is shown in Figure 8. At the left two noises of equal intensity are sounded separately and then simultaneously. The total intensity is merely the sum of the individual intensities. If this situation is expressed in terms of decibels, as at the right, the normal rules of addition no longer hold. We see that 56 decibels plus 56 decibels is 59 decibels, not 112 decibels.

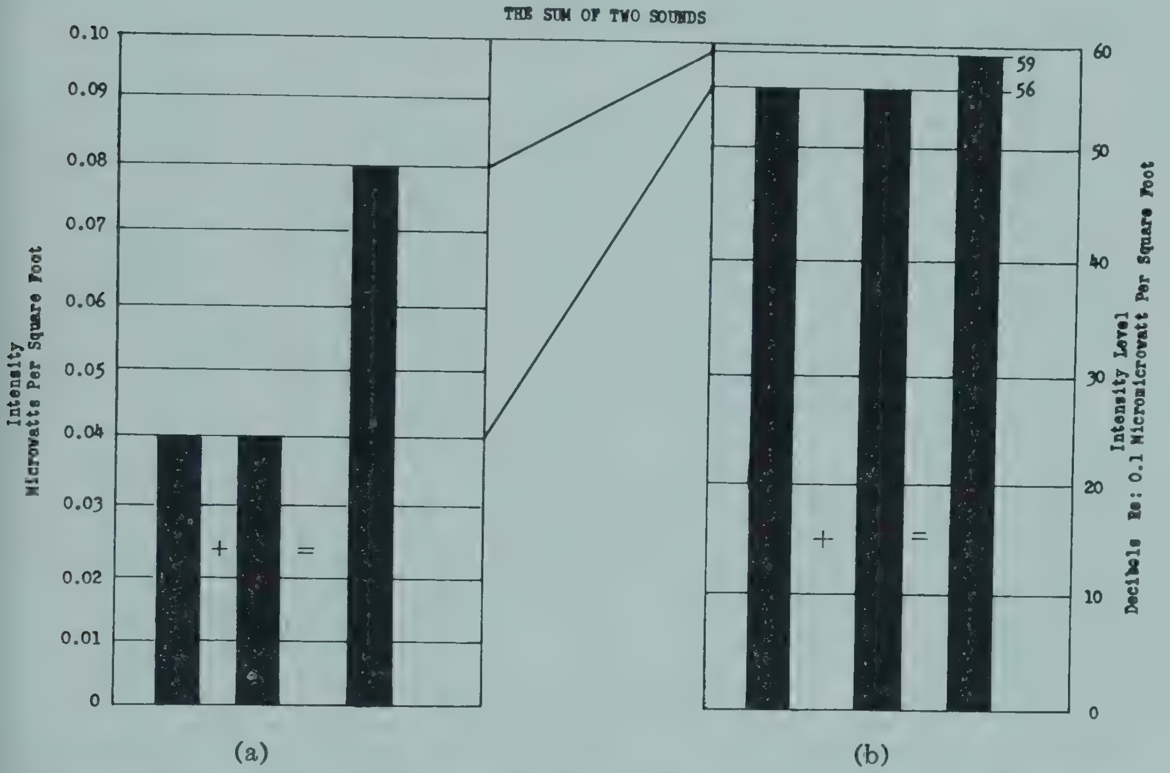


Figure 8. A graphical demonstration of the result of combining two sounds of equal intensity (a) on a linear scale and (b) on a logarithmic scale.

Thus the unit of the decibel is a great deal more complex than those with which we are familiar. It varies in range of absolute pressure or intensity depending on the portion of the scale; it cannot be manipulated according to the normal rules of arithmetic; and it bears no direct relation to a person's subjective reaction to sounds.

M. INTENSITY LEVEL

The decibel is a unit that has many uses throughout electrical engineering acoustics, and hearing. So far we have been discussing its use in connection with the measurement of intensity levels. (The word "level" is used whenever a quantity is expressed on a decibel scale.) The mathematical definition in this case is:

$$\text{Intensity level} = 10 \log_{10}(I/I_0) \tag{3}$$

This equation states that the intensity level in decibels is equal to ten times the logarithm to the base ten of the ratio of the intensity I and the reference intensity I_0. If the intensity is expressed in $\mu\mu$watts per square foot, the reference intensity will be 0.093, which usually is rounded off to 0.1.

TABLE 2a

Comparison of Sound Measurement Scales

Intensity (watts/sq. ft.)	Intensity level (db)	Sound pressure level (db)	R.M.S. sound pressure (μbars)
1.0	130	130	
0.1	120	120	200
0.01	110	110	
0.001	100	100	20
0.000,1	90	90	
0.000,01	80	80	2
0.000,001	70	70	
0.000,000,1	60	60	0.2
0.000,000,01	50	50	
0.000,000,001	40	40	0.02
0.000,000,000,1	30	30	
0.000,000,000,01	20	20	0.002
0.000,000,000,001	10	10	
0.000,000,000,000,1	0	0	0.000,2

A comparison of the intensity scale and the intensity level scale is shown in Table 2a and the details of the range between 100 db and 120 db in Table 2b. It will be observed that in Table 2b the relationship between the last digit in the number of decibels and the figures in the value of intensity is always the same; only the decimal point changes in each set of 10 decibels. Thus it is possible to say that the last digit in the number of decibels indicates the numbers involved, and the remaining digits indicate the location of the decimal point. A simple method of adding intensity levels utilizes Table 3. The addition of intensity levels shown in Figure 8 is an example. Here the excess of the stronger component was 0 decibels since both intensity levels were 56 decibels, adding 3 decibels gave a combined intensity level of 59 decibels.

TABLE 2b

Detail of Range between 100 db and 120 db

Intensity (watts/sq. ft.)	Intensity level (db)	Sound pressure level (db)	R.M.S. sound pressure (μbars)
0.1	120	120	200
0.063	118	118	160
0.04	116	116	128
0.025	114	114	100
0.016	112	112	80
0.01	110	110	64
0.0063	108	108	50
0.004	106	106	40
0.0025	104	104	32
0.0016	102	102	25
0.001	100	100	20

TABLE 3

Increments for Combining Intensity Levels

Excess of stronger component (db)	Add to the stronger to get combined level (db)
0	3.0
1	2.5
2	2.0
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.7
9	0.6
10	0.5

Often it is necessary to add several intensity levels together at the same time: for instance, to check the over-all intensity level against the sum of the individual octave-band intensity levels. The sum is obtained by making seven consecutive additions so that one band intensity is combined with the total intensity level of all bands previously combined. Quite often it is possible to eliminate unimportant bands by starting with the bands with the highest intensity levels. After some practice it is possible to make a rough mental calculation of the over-all intensity level from the octave band levels.

Through common usage the words *decibels* and *noise level* have come to be synonymous with *intensity level*. Actually one should report the *intensity level* of a certain *noise* in *decibels*.

N. SOUND PRESSURE LEVEL

In addition to its use in the measurement of intensity levels the decibel is used as the unit of sound pressure level. The mathematical definition for this quantity is:

$$\text{Sound pressure level} = 20 \log_{10}(p/p_0) \tag{4}$$

This equation is similar to equation 3 except that the logarithm of the ratio of the pressure p to the reference sound pressure p_0 is multiplied by a factor of 20 instead of 10. If p is the r.m.s. pressure in μbars, the reference pressure p_0 will be 0.0002.

In many cases, the intensity level and the sound pressure level will be equal. To demonstrate this, it is necessary to note that under the conditions that sound intensity may be expressed in terms of sound pressure (equation 2), both the intensity reference, I_0, and the pressure reference, p_0, are equivalent to the quietest sound that one can hear (Section I.G). Thus, when a sound field is such that equation 2 is correct it can be shown that $(p/p_0)^2 = I/I_0$. If this ratio is substituted in equation 3 it will be seen that the intensity level is equal to the sound pressure level:

$$\begin{aligned} \text{Intensity level} &= 10 \log_{10}(I/I_0) \\ &= 10 \log_{10}(p/p_0)^2 \\ &= 20 \log_{10}(p/p_0) \\ &= \text{sound pressure level} \end{aligned}$$

Therefore, the equivalency of sound pressure level and sound intensity level will hold under the conditions that are required for equation 2. That is, measurements must be made at locations that are neither too close to the sound source nor too close to reflecting objects. Although these conditions are rarely met precisely, the difference between sound pressure level and intensity level is usually small enough that the two may be used almost interchangeably. This convenient situation is a result of a careful choice in the definition of the two quantities and the selection of equivalent references. The reader should realize that the contrivance that makes the two kinds of levels equal has no effect on the intensity and the sound pressure themselves. Microbars and microwatts per square foot are in no sense equivalent units, and there is no reason to expect that the sound pressure and the intensity will be numerically equal.

The relationship between the sound pressure and the sound pressure level is shown in Table 2. As discussed above, the intensity level and the sound pressure level are numerically equivalent under most practical circumstances. This fact is signified by the dotted lines connecting these two scales. Although microphones respond to sound pressure, the combination of the various components of a noise and the transmission of noise may be viewed rather simply in terms of the intensity. For this reason the discussions that follow will be in terms of intensity or intensity level whenever it is more convenient.

O. SOME COMMON SOUNDS

In order to convey to the reader some idea of what various intensity levels mean in terms of his listening experience a number of common sounds have been plotted in Figure 9. In each case octave band analyses are shown. Notice that the over-all intensity level of the sound does not necessarily correspond to the subjective reaction to the sound or to the hazard to hearing. For instance, the over-all intensity level measured in an airplane is higher than that in a weaving room. However, the weaving room presents a more serious problem from the viewpoint of subjective reaction to the noise, the ability to communicate in the noise, and the possible hearing impairment resulting from the noise. Therefore, we can conclude that, without additional information, the over-all intensity level is a very crude indicator of the severity of a noise problem.

Careful study of the octave band measurements shown in Figure 9 should give the reader some feeling for the mysterious decibel unit. A level of 40 db or 50 db is rather quiet when the sound energy is concentrated in the low frequency bands, but moderately loud when concentrated in the high frequency bands. Under the most perfect conditions persons with excellent hearing cannot detect a sound whose intensity level is much below 0 db even in the most sensitive regions of hearing between 1200 and 4800 c.p.s. Communication even by shouting becomes difficult or impossible as the intensity level in the bands between 600 and 4800 c.p.s. approaches 90 to 100 db. Exposure for even short periods to levels such as those measured in a jet engine test cell (Figure 9) can be quite painful and can cause a hearing impairment that may not disappear until weeks or months later.

The measurements given in Figure 9 show the approximate limits of our hearing experience from low intensity sounds to high intensity sounds and from low frequency sounds to high frequency sounds. The area indicated in this figure represents, therefore, the field of interest to the noise-control engineer.

II. The Transmission of Sound

The transmission of sound through the air is accomplished by the microscopic movements of air molecules which, in turn, cause variations in the density and pressure of the atmosphere. Although the sound travels almost instantaneously from one side of the room to the other, the molecules that carry the sound wave move less than the breadth of a hair. Probably the best way to visualize the motions of the molecules in transmitting sound waves is by analogy to waves on the surface of a body of water. These waves may come rolling into shore, but any individual portion of the water moves only slightly. That this is true can be proved easily by watching the motion of a cork on the waves. It merely bobs up and down as the waves pass under it. Thus we see that the undulating motion of the water is responsible for the visual effect that the water moves along with the waves.

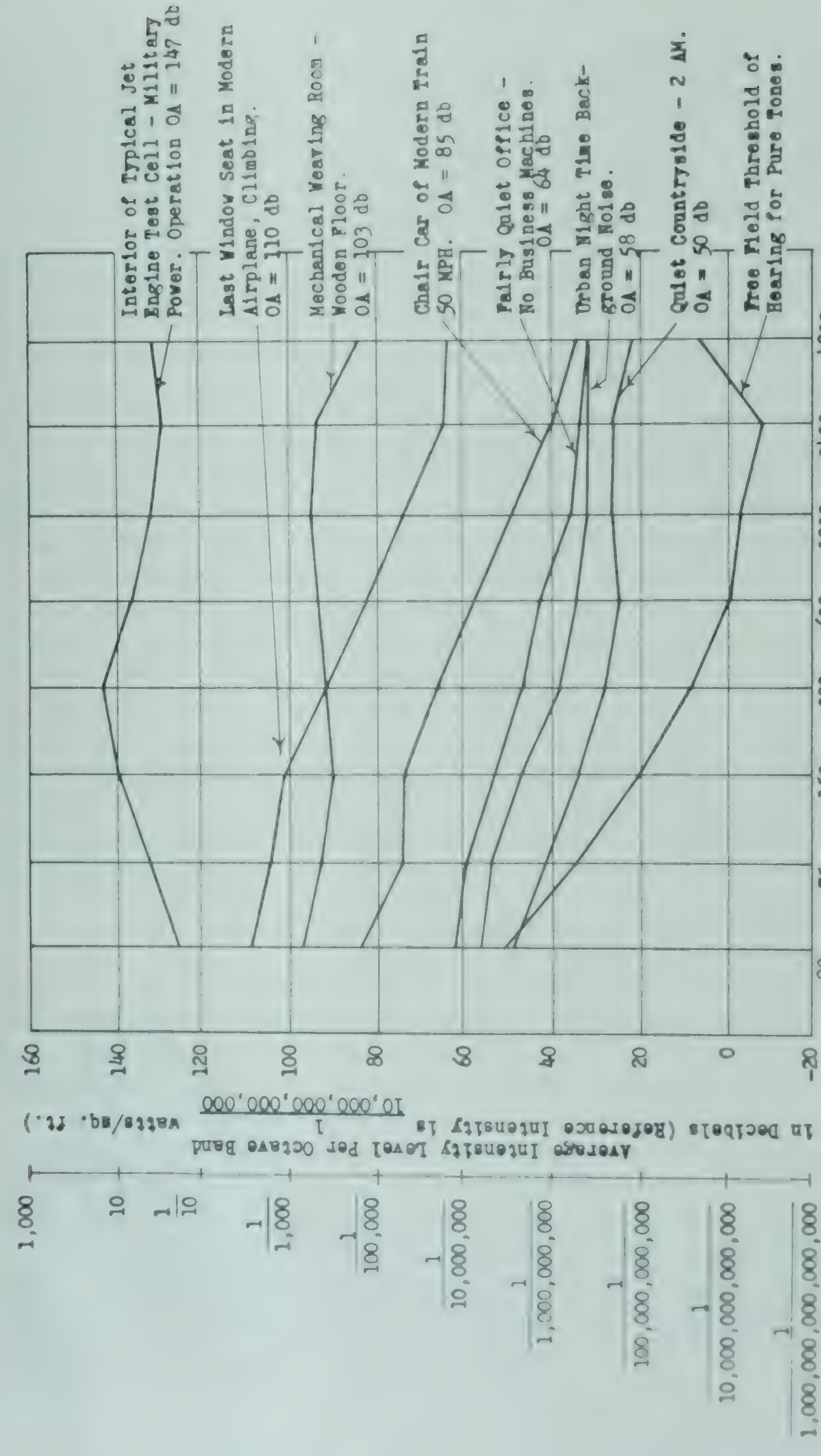


Figure 9. Octave band measurements of several common sounds.

A. RADIATION FROM A SIMPLE SOUND SOURCE

One of the simplest examples of the transmission of sound is that from a tuning fork. When it is struck the vibration of the tines produces sound waves that radiate uniformly in every direction. Again it may be helpful to use the analogy of a body of water: the motion of the waves on a still pond resulting from dropping a pebble. The crests of the waves radiate outward in ever-increasing circles. If it were possible to drop a series of pebbles with proper timing we might observe a pattern something like that shown in Figure 10. Here the width of the black rings is intended to indicate the height of the wave. Note that the width decreases as the diameter increases. Naturally this is a picture of the surface of the body of water at only one instant. Since the waves are traveling outward each ring will expand rapidly until it takes the place of the next larger ring shown in the figure. This process will continue over and over again so that the picture will appear to be always changing, yet always the same.

Sound waves radiated from a tuning fork also can be represented by the rings shown in Figure 10. Of course, since the sound wave travels in all directions, there will be a pattern similar to this in the vertical plane or in any other plane that we wish to choose. We have, therefore, instead of a set of expanding circular rings, a set of expanding spherical shells. We may interpret Figure 10 as a cross section of these expanding spherical shells.

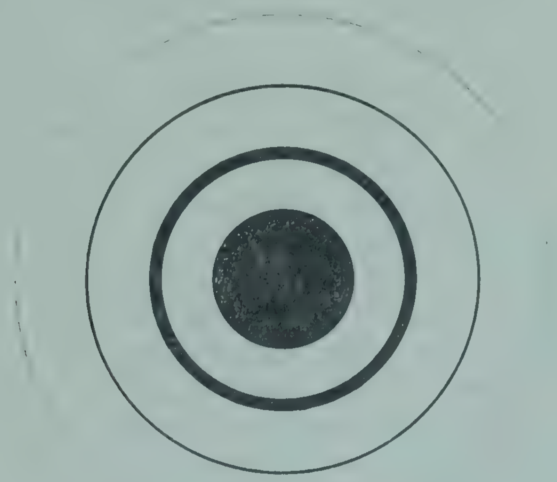


Figure 10. A graphical representation of the radiation of sound from a simple source in free field.

B. THE INVERSE-SQUARE LAW

In the case of the sound wave the thickness of the shell corresponds to the intensity of the sound. Since the intensity is the sound power being transmitted through a unit area, to compute the total sound power radiated by the tuning fork through a certain area it is only necessary to multiply the value of the intensity by the number of square feet in the area. For instance, if the tuning fork produces a sound intensity of 1 μwatt per square foot at the surface of a hypothetical sphere surrounding the source and the area of this sphere is 10 square feet, the total power radiated by the tuning fork will be 10 μwatts.

Since the surface area of a sphere is 4 π times the square of the radius, the total power radiated by any simple source in free space will be:

$$\text{Sound power} = 4\,\pi r^2 I$$

Note that the intensity, I, measured r feet from the source must vary inversely as the square of this distance in order that the sound power radiated by the source remain unchanged. This is the well-known inverse-square law of acoustics. From this law it follows that the intensity must drop to one quarter for each doubling of the distance. In terms of intensity level each doubling of distance from a source is equivalent to 6 db drop in the level. This can be checked by noting that dividing the value on the intensity scale by four (Table 2b) is equivalent to a 6 db drop in the intensity level.

C. SOUND IN A ROOM WITH NONABSORBING WALLS

In a room with hard, sound-reflecting walls the radiation of sound is quite different from that shown in Figure 10. Whenever any obstacle is placed in the path of a sound wave, a reflected wave is produced. The intensity of this reflected wave will depend upon the composition of the obstacle. If it is hard and nonporous, the intensity of the reflected wave will be practically equal to the incident wave.

When a sound source is completely enclosed in a room with hard walls, the sound will be reflected back and forth from wall to wall many, many times. A sound that undergoes these multiple reflections is said to reverberate about the room. Such a reverberant condition is shown in Figure 11 where, as before, the thickness of the rings indicates the intensity of the sound. Near the source the direct sound predominates, but at points closer to the walls the multiple reflections generate a rather random sound field. This situation is completely different from a sound source in an empty space (Figure 10). In the reverberant part of the sound field the sound waves come from all directions and the average sound intensity is almost uniform. The part of the field that is close to the sound source and resembles the field in Figure 10 is called the direct or free field. The part of the field that is characterized by sound travelling in all directions, the diffuse or random part, is called the reverberant sound field.

In the reverberant field the reflected sound is of primary importance, and the sound radiated directly from the source is practically negligible. The relation between sound intensity and sound pressure shown in equation 2 no longer holds since it is derived for free-field conditions. The equivalency between sound pressure level and intensity level (Table 2) will also be invalid because in reverberant sound fields the intensity level is 6 db less than the sound pressure level.

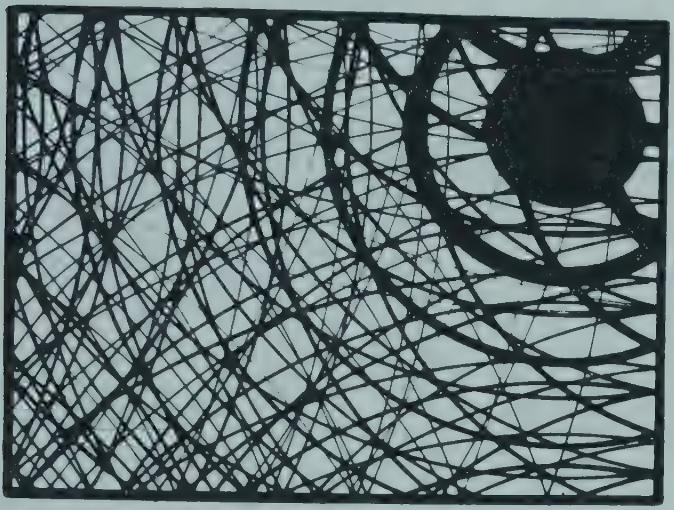


Figure 11. A graphical representation of the radiation of sound from a simple source in a reverberant room.

D. THE ABSORPTION OF SOUND

A soft, porous material, with a vast number of tiny but interconnected air spaces, is likely to absorb a large share of the sound that falls on it. The sound energy is converted into heat, but at normal intensities the resulting temperature rise is insignificant.

No material can absorb more sound than falls upon it. The pleasant picture of absorbing material sucking sound from the air is totally inaccurate. A material that will absorb sound as well as does an open window is optimum. Special shapes and arrangements are required for small local improvements over this optimum absorption and even these "superabsorbers" are no better than an open window when an average absorption over a large area is considered.

It is clearly foolish, therefore, to enclose a noisy machine with an absorbing material in an effort to reduce the sound *inside* the enclosure. The best sound absorption already surrounds the machine: empty space! This is the situation that exists in the tuning fork example shown in Figure 10. The sound source is completely surrounded by empty space and, therefore, no reflected sound waves are present.

E. THE ABSORPTION COEFFICIENT

Part of the sound that falls on any material is absorbed and part is reflected. If most of the sound is reflected, the material is nonabsorbing and is likely to have a hard, impervious surface like that of metal, bricks, concrete, or plaster. If very little of the sound is reflected, the material is absorbing and is likely to have a soft, porous surface like that of carpeting, glass wool, or snow. The fraction of incident sound intensity that is absorbed by a surface is called the absorption coefficient, α (alpha). An open window has an absorption coefficient of 1, whereas a piece of marble has an absorption coefficient very nearly zero.

The absorption coefficient, α, of most materials is not the same for all frequencies. This is especially true of the "acoustical materials," which are designed for high absorption. Figure 12 shows the absorption coefficient for several materials in the audible frequency range. Published tables are available giving data on other materials.[5-7] There is no single ideal absorbing material; one must be chosen with characteristics that are best for the particular problem at hand.

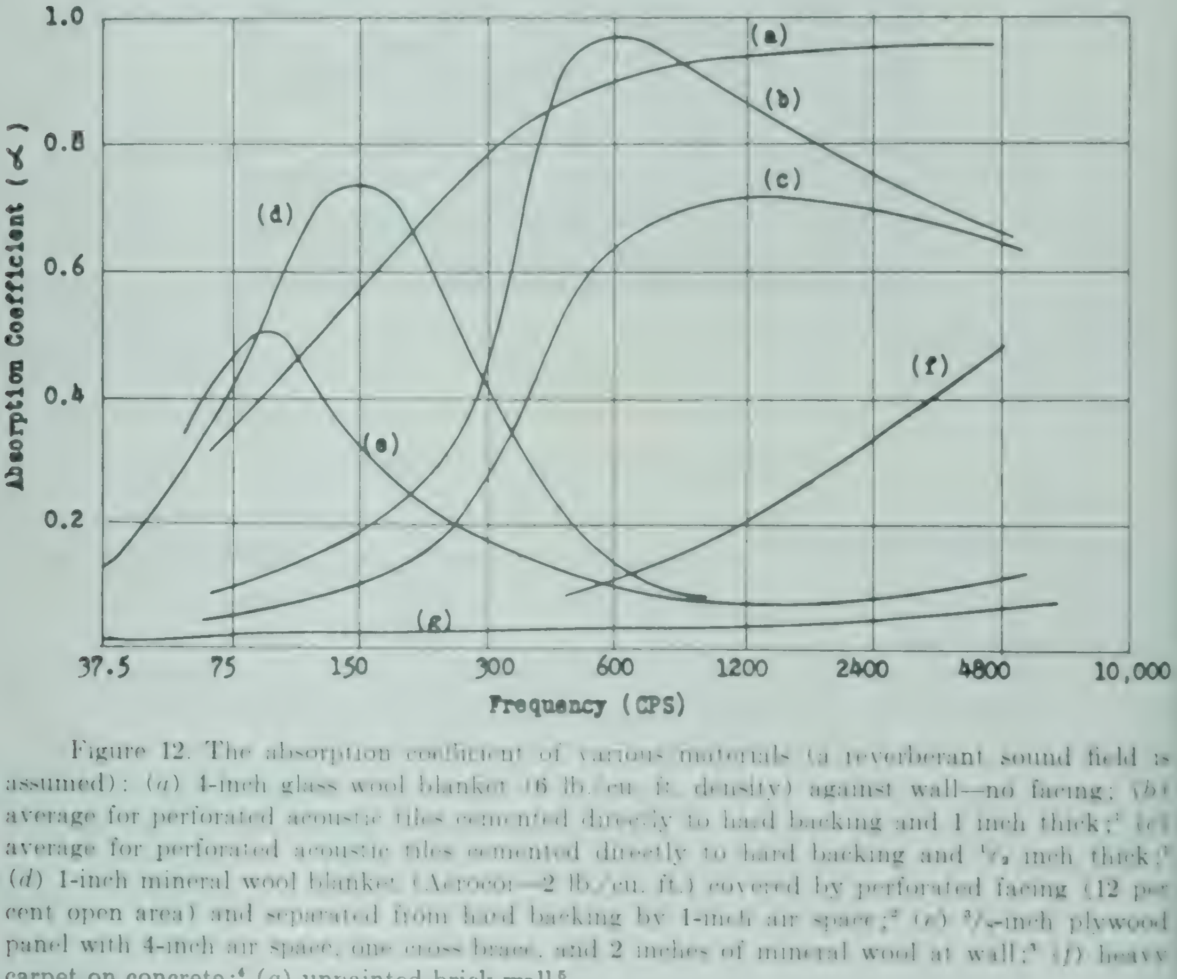


Figure 12. The absorption coefficient of various materials (a reverberant sound field is assumed): (*a*) 4-inch glass wool blanket (6 lb./cu. ft. density) against wall—no facing; (*b*) average for perforated acoustic tiles cemented directly to hard backing and 1 inch thick;[3] (*c*) average for perforated acoustic tiles cemented directly to hard backing and $\frac{1}{2}$ inch thick;[3] (*d*) 1-inch mineral wool blanket (Aerocor—2 lb./cu. ft.) covered by perforated facing (12 per cent open area) and separated from hard backing by 1-inch air space;[2] (*e*) $\frac{3}{8}$-inch plywood panel with 4-inch air space, one cross brace, and 2 inches of mineral wool at wall;[3] (*f*) heavy carpet on concrete;[4] (*g*) unpainted brick wall.[5]

The average absorption coefficient, $\bar{\alpha}$, of a room is a good indicator of the nature of the sound field within that room. One may calculate $\bar{\alpha}$ by multiplying α for each material in the room by the total number of square feet of wall surface that is covered by that material, adding all such products, and dividing the total by the surface area of the room. This computation is shown in equation 5.

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[2] U. Ingard and R. H. Bolt, Absorption characteristics of acoustic material with perforated facings, *J. Acoust. Soc. Am.*, **23**, 533 (1951).

[3] P. H. Parkin and H. J. Purkis, Sound absorption of wood panels for the Royal Festival Hall, *Acustica*, **1**, 81 (1951).

[4] B. C. Purcell, private communication to the author.

[5] V. O. Knudsen and C. M. Harris, *Acoustical Designing in Architecture*, Wiley, New York, 1950.

[6] *Sound Absorption Coefficients of Architectural Acoustical Materials*, Acoustical Materials Association, 205 W. Monroe St., Chicago, Ill. (published periodically).

[7] Sound absorption coefficients of the more common acoustical materials, *Natl. Bur. Standards Bull.*, Letter Circular **LC 870**.

$$\bar{\alpha} = \frac{S_1\alpha_1 + S_2\alpha_2 + S_3\alpha_3 + \ . \ . \ . \ .}{S_1 + S_2 + S_3 + \ . \ . \ . \ .} \tag{5}$$

Here, α_1, α_2, α_3, and so forth, are the absorption coefficients of the various materials in the room and S_1, S_2, S_3, and so forth, are the surface areas of these materials, respectively. Naturally, the entire surface of the room including ceiling and floor should be accounted for in this calculation.

As an example, determine the average absorption coefficient, $\bar{\alpha}$, at 600 c.p.s., of a cubical room with 1-inch acoustical tile on the ceiling ($\alpha = 0.95$), brick walls ($\alpha = 0.03$), and a carpet on the floor ($\alpha = 0.37$). Since each side of the cube has an area equal to $^1/_6$ of the total area, the computation is as follows:

$$\alpha = \frac{0.95l^2 + 0.37l^2 + 0.03\ (4l^2)}{6l^2} = 0.24$$

where l is the length of a side of the cube.

F. SOUND IN A ROOM WITH ABSORBING WALLS

When absorbing material is placed on the walls of a room, less sound is returned to the room after each reflection. The sound that is absorbed by the wall is transformed into heat and can never return to the room. If the walls of the room were perfectly absorbing the situation would be exactly the same as that shown in Figure 10 because there would be no reflected sound. If, however, some small fraction is returned to the room after each reflection, the sound field will be intermediate between the free field (Figure 10) and the reverberant field (Figure 11. An example of this intermediate situation is shown in Figure 13. The average absorption coefficient that has been assumed for this example is 0.9.

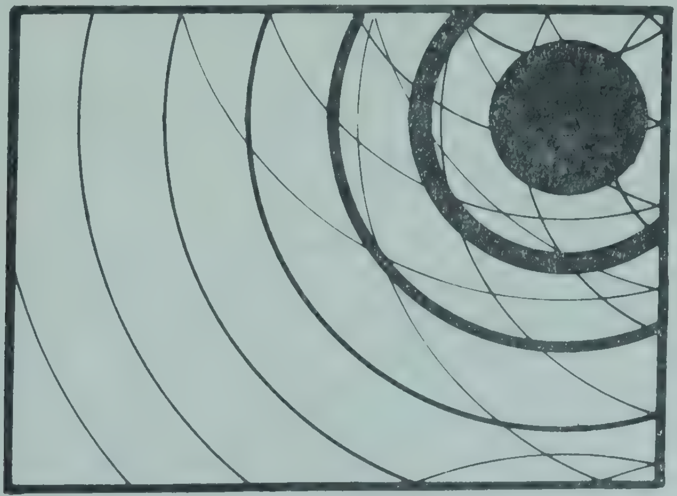

Figure 13. A graphical representation of the radiation of sound from a simple source in a room with absorbing walls.

Under certain conditions it is possible to calculate the approximate sound pressure level produced in various parts of a room as a result of a simple sound source near the center of the room.[8] The results of these calculations for rooms having various average absorption coefficients, $\bar{\alpha}$, are shown in Figure 14. The horizontal axis is the distance, r, from the source to the pressure-measuring microphone divided by the radius, r_0, of a sphere whose surface area is the same as that of the room: that is, $r_0 = \sqrt{\text{surface area}/4\,\pi}$. For example, the radius of

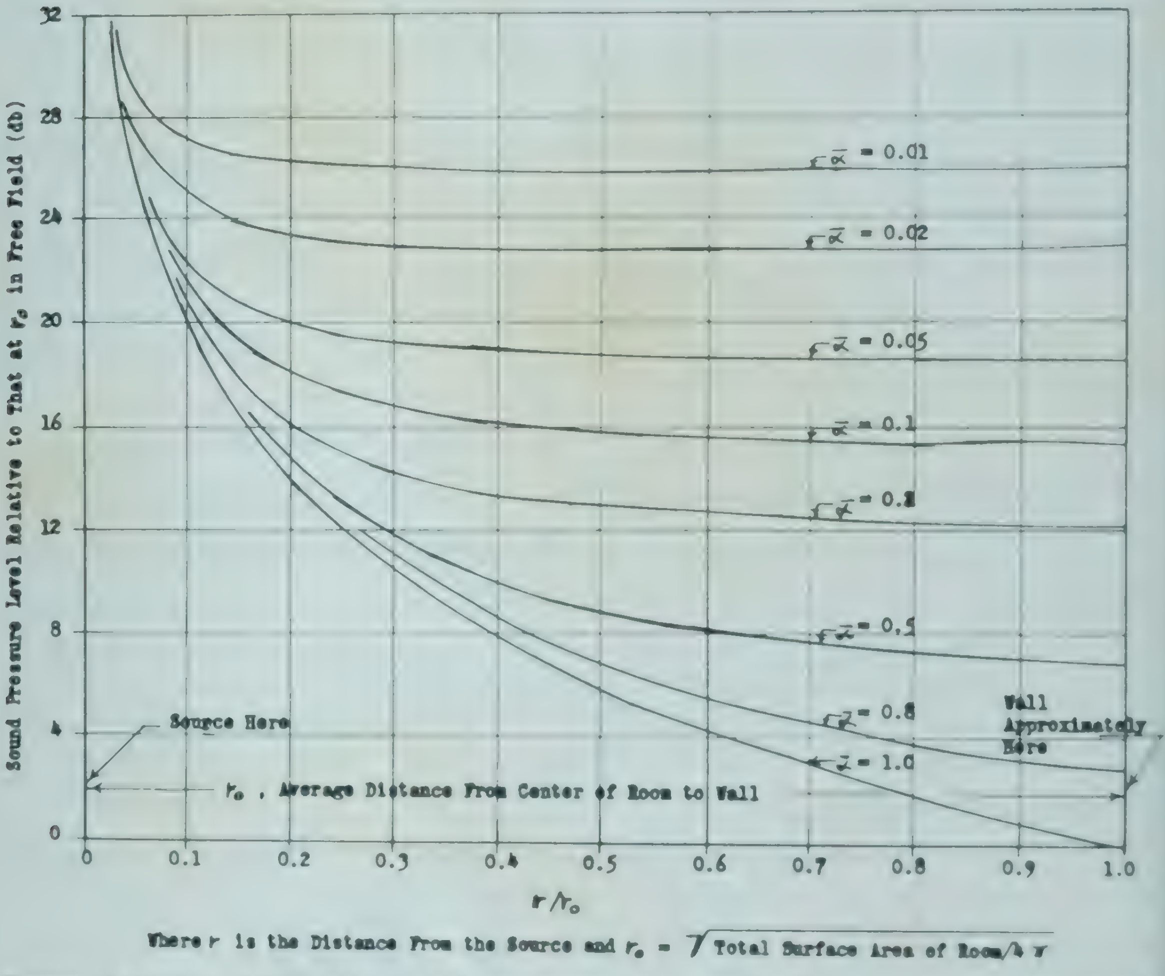

Figure 14. Curves showing the variations in sound pressure level in rooms with partially absorbing walls.

a sphere whose surface area is the same as that of a cube will be $r_0 = \sqrt{6l^2/4\pi} = 0.69l$, where l is the length of a side of the cube. The vertical axis of Figure 14 shows the increase in sound pressure level that exists at any point in the room over the sound pressure level that would exist at r_0 with the source radiating into free space. The various curves on this chart are drawn for average absorption coefficients, $\bar{\alpha}$, between 0.01 and 1.

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[8] H. F. Hopkins and N. R. Stryker, A proposed loudness-efficiency rating for loudspeakers and the determination of system power requirements for enclosures, *Proc. Inst. Radio Engrs.* **36**, 315 (1948).

The curves in Figure 14 show that there are two distinct parts of the sound field in a room. In the reverberant part of the field the sound pressure level is independent of location. However, closer to the source the field behaves like that of a source in free space. For many practical sources this free field does not extend all the way to the source. In these cases a third kind of field exists called the near field. Without a detailed knowledge of the sound source itself, it is impossible to predict the sound pressure level in the near field of a sound source.

The curves shown in Figure 14 will hold only when both the sound source and the pressure-measuring microphone are located at least one half of a wave length away from the walls. Thus, if the room is very small or the frequency very low, there will be large portions of the room in which Figure 14 will give incorrect results. In addition, the curves will be more nearly correct for a source that radiates wide-band noise than for one that radiates a pure tone.

G. THE TRANSMISSION OF SOUND THROUGH PARTITIONS

So far the discussions have centered upon the transmission of sound from a source to some point in the space surrounding the source. If the sound source is, in some way, partitioned off from the measuring microphone, the transmission of sound will, as a rule, be drastically reduced.

There are important exceptions to this rule. For example, "acoustical materials" will not cause large reductions in the sound transmitted through them. Unfortunately, there is some confusion about this matter resulting from the fact that a good sound absorber is often a good heat insulator. The heat-insulating properties of the material are derived from the air trapped in the many tiny air spaces. It is difficult for a current of hot air to move through the material and, therefore, it is possible to take advantage of the poor heat conductivity of a stationary air mass. Some materials have no connections between the air spaces and as a result are very good heat insulators, but poor sound absorbers.

The word *insulation* should have no application in acoustics or noise control. It is often erroneously associated with quieting because many manufacturers claim that their (heat) insulating material has good acoustical properties. They mean that it is a good sound absorber. The public, however, often concludes that the material will transmit but a small amount of the sound incident upon it. In other words, the consumer assumes that the heat-insulating material will provide excellent sound isolation. As we can see from Figures 15, 16, and 17, this is not the case. The intensity of the sound is reduced as a result of passage through the absorbing material, but considerably greater reductions can be obtained with less expensive materials. Figure 15 demonstrates the effect of a 4-inch thick glass fiber blanket weighing 6 pounds per cubic foot. The frequency is 250 c.p.s. Most sound-absorbing materials are either thinner or less dense so that a larger fraction of the incident sound is transmitted than is shown in Figure 15.

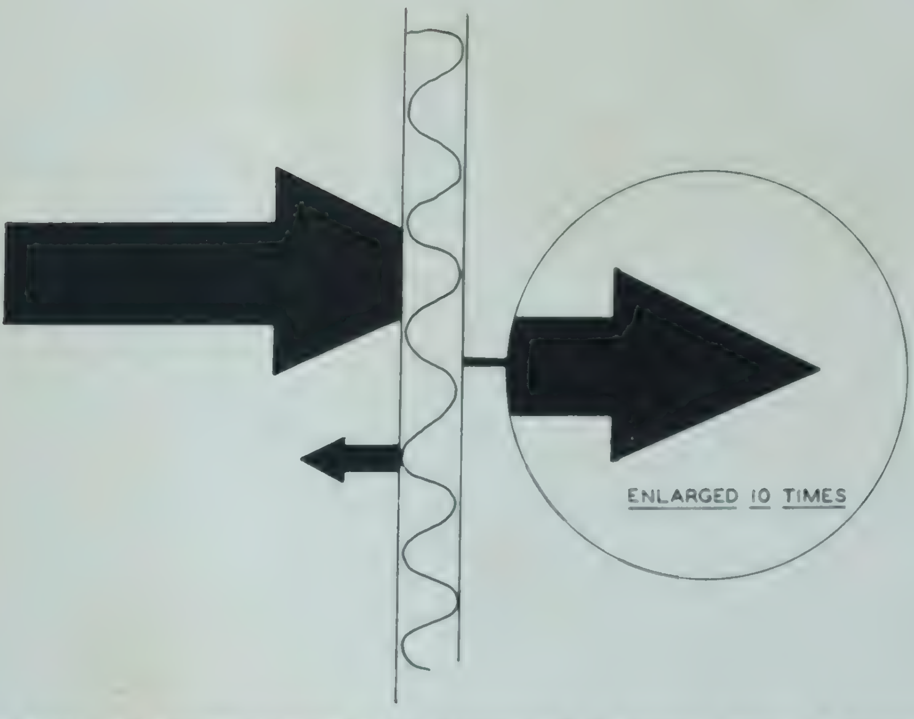

Figure 15. A graphical representation of the transmission of sound through a sound-absorbing material.

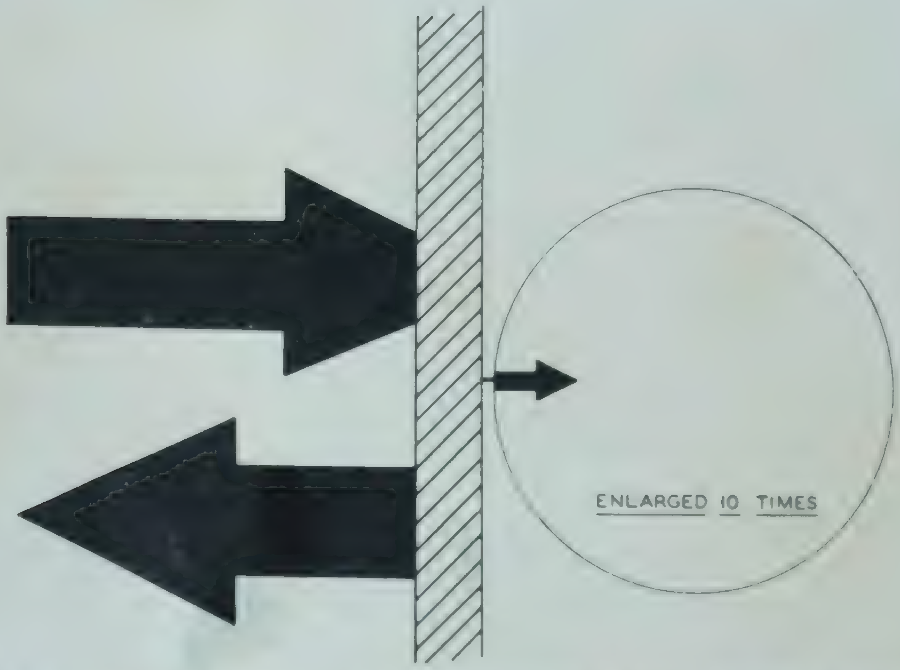

Figure 16. A graphical representation of the transmission of sound through a solid partition.

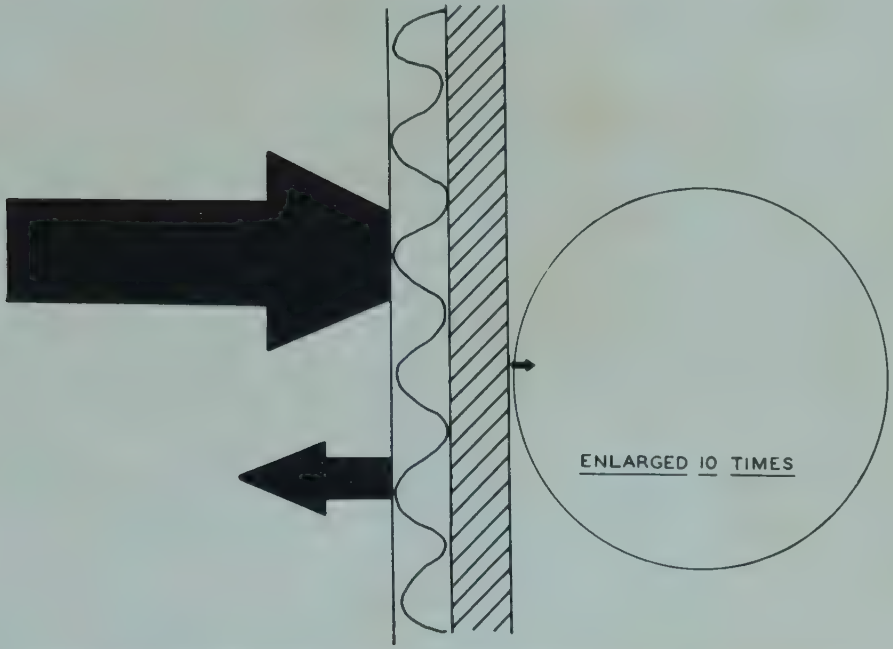

Figure 17. A graphical representation of the transmission of sound through a combination of sound-absorbing material and a solid partition.

In order to have good sound isolation between two spaces, it is necessary to separate them by a relatively heavy, impervious material, such as metal, masonry, or wood. The heavier the material, the more difficult it becomes for the incident sound wave to produce any vibration of the wall. It is the vibration of the wall that causes sound to be radiated into the adjoining space. Figure 16 shows schematically the effect of such a sound-isolating partition. The example chosen is $^1/_2$-inch plywood (weighing about 2 pounds per square foot), which gives a reflected sound almost as intense as the incident sound. The reflections on the left of the partition will cause a reverberant field to be built up like that shown in Figure 11. The increase in the intensity over that shown for a wall covered with absorbing material (Figure 13) will cause added vibration of the partition.

Better sound isolation between the two rooms can be obtained if the reverberant build-up in the first room is eliminated. The partition shown in Figure 17 combines the advantages of an absorbing material to reduce reverberation and a heavy, impervious panel to reduce the transmission of sound. With this combination one can obtain the optimum sound isolation possible with single-wall construction. Incidentally, the absorption coefficient here does not correspond to that shown for the same material in Figure 12 because the sound field in this example is not reverberant. This combination of sound-absorbing and sound-isolating materials is the basic component of most designs for the control of air-borne noise. Often a protective facing is placed in front of the absorbing material to prevent damage. Usually this facing is a perforated material, such as sheet metal, pressboard, or gypsum board, but sometimes a thin plastic or glass wool bag may be used. A properly protected wall structure finds wide application in noise control problems.

H. THE MASS LAW

The transmission of sound through partitions is a result of the following chain of events. The sound pressure on the side of the partition toward the sound source causes an alternating force to press and pull the wall back and forth. The motion of the wall then generates a new sound wave on the side of the partition away from the sound source. The sound pressure that is generated will depend upon the vibrational velocity of the partition. The distance that the wall moves is microscopic, but its motion is rapid enough to cause compressions and rarefactions in the air.

The theoretical reduction in intensity level from one side of a partition to the other is shown in Figure 18. It is assumed that the reflected sound on the source side of the partition predominates, but that reflected sound on the other side is unimportant. The transmission loss (difference between the incident intensity level and the transmitted intensity level) increases with both frequency and surface density (weight of the partition in pounds per square foot), as shown by the several curves. High values of transmission loss occur when the motion of the

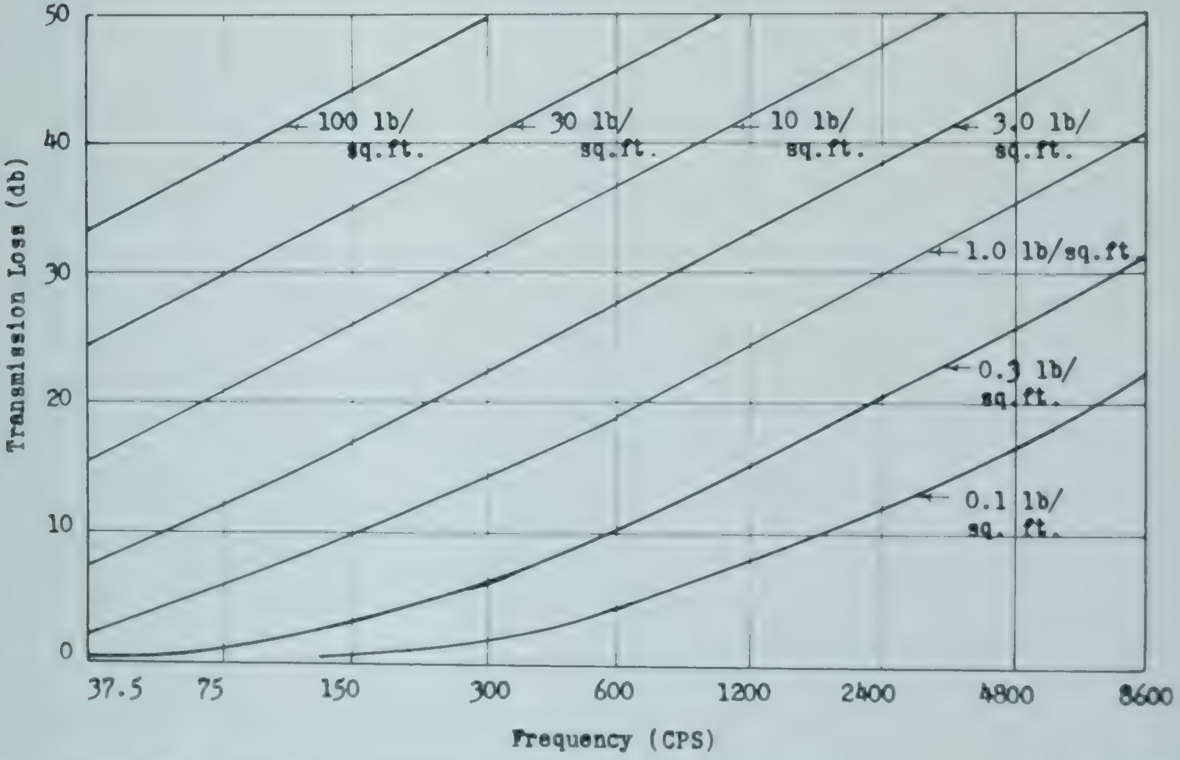

Figure 18. The theoretical transmission loss for impervious, well-damped partitions of various surface densities. A reverberant sound field is assumed on the source side of the partition

partition is small as a result of either a heavy wall or high frequencies. The transmission of vibrations through other paths that flank the partition usually limits the maximum transmission loss to about 50 or 60 db, however.

Table 4 lists the surface density of several common materials. Fiberboard and, consequently, acoustical tiles, are poor materials for sound isolation because of their light weight. It is easy for the sound wave to set a partition of this sort in motion and thereby excite sound waves on the opposite side. The fact that the material absorbs sound is of no consequence. An examination of the heavier building materials listed shows that brick, concrete, and cement-block walls are the best sound isolators.

TABLE 4

Surface Density of Building Materials

(Per inch of thickness except those with an asterisk)

Material	Surface density (lb./sq. ft.)
Aluminum	14
Brick	10–12
Building boards	
Gypsum board	4–5
Pressboard	5–6
Plywood	3
Fiberboard	1–2
Cement and asbestos board	9–10
Concrete	
Dense	12
Cinder	6–8
Cinder block wall, 4 inches thick	19*
Cinder block wall, 9 inches thick	37*
Concrete block wall, 9 inches thick	54*
Concrete block wall, 12 inches thick	73*
Glass	13
Lead	65
Plaster	
Gypsum (sanded)	9–13
Lime	7
Vermiculite	3–4
$^1/_2$-inch Gypsum plaster on wood lath	8*
Plexiglas	6
Sand	7–10
Steel	40
Stone (limestone, granite, or marble)	14
Wood	
Pine	2–3
Maple	4

In many situations it would be advantageous to install a light-weight sound-isolating partition. Unfortunately, it is extremely difficult to construct a partition that will give any more isolation than that indicated by the mass law curves shown in Figure 18. A double wall, when properly constructed, will overcome this difficulty. However, the two portions of the wall must be completely isolated from each other. It is necessary that no appreciable vibration travel from the wall facing the sound source through any path whatsoever to the second wall. Methods for accomplishing the necessary vibration isolation are described in other texts and will not be reviewed here.[5,9]

I. TRANSMISSION OF SOUND THROUGH COMPOSITE STRUCTURES

When the partition separating a noisy area from another area is made up of two or more materials, each having a different surface density in pounds per square foot, an effective transmission loss for the entire partition can be computed. This is done by finding the power transmitted through each portion of the partition, adding these figures, and dividing by the total area of the partition. This gives the average intensity transmitted through the composite wall structure; its difference from the intensity on the source side is the transmission loss.

The effective transmission loss of a partition composed of two different materials is shown in Figure 19. Along the horizontal axis is the difference in transmission loss of the two portions of the partition. The several curves correspond to the area of the portion with the smaller transmission loss expressed as a fraction of the total area. The point on the vertical axis that corresponds to the intersection of the correct difference in transmission loss and the correct fractional area curve gives the number of decibels that must be subtracted from the larger transmission loss in order to get the effective value for the composite structure. The curves of Figure 19 may also be used if the wall in question is constructed of more than two different materials. In this case, one should find the combined transmission loss for any two portions of the wall. Then proceed by combining this effective value with the transmission loss of another portion, and so on.

The curves of Figure 19 emphasize a very important point in connection with the design of an isolating wall. A tiny portion of a wall constructed of material of low transmission loss tends to nullify the effect of the remainder of the wall. In order to clarify this point, consider the transmission loss of a concrete block partition 10 feet high. Figure 18 and Table 4 show that this structure should yield a transmission loss of 48 db at about 600 c.p.s. Suppose that the mason did not realize the importance of small cracks in a noise control structure, and carelessly left on opening just $^1/_8$ inch wide along the top of the wall. The area ratio between this small opening and the rest of the wall is about 0.001, but the difference in the transmission loss between the two is, of course, 48 db. Figure 19 shows that 18 db must be subtracted and that the effective transmission loss will be 30 db, substantially less than would be expected for the concrete wall.

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[9] R. H. Bolt, L. L. Beranek, and R. B. Newman, Handbook of acoustic noise control: I. Physical Acoustics, *Wright Air Development Center Tech. Rept.* **52-204**, Wright-Patterson Air Force Base, Ohio, 1, 1952.

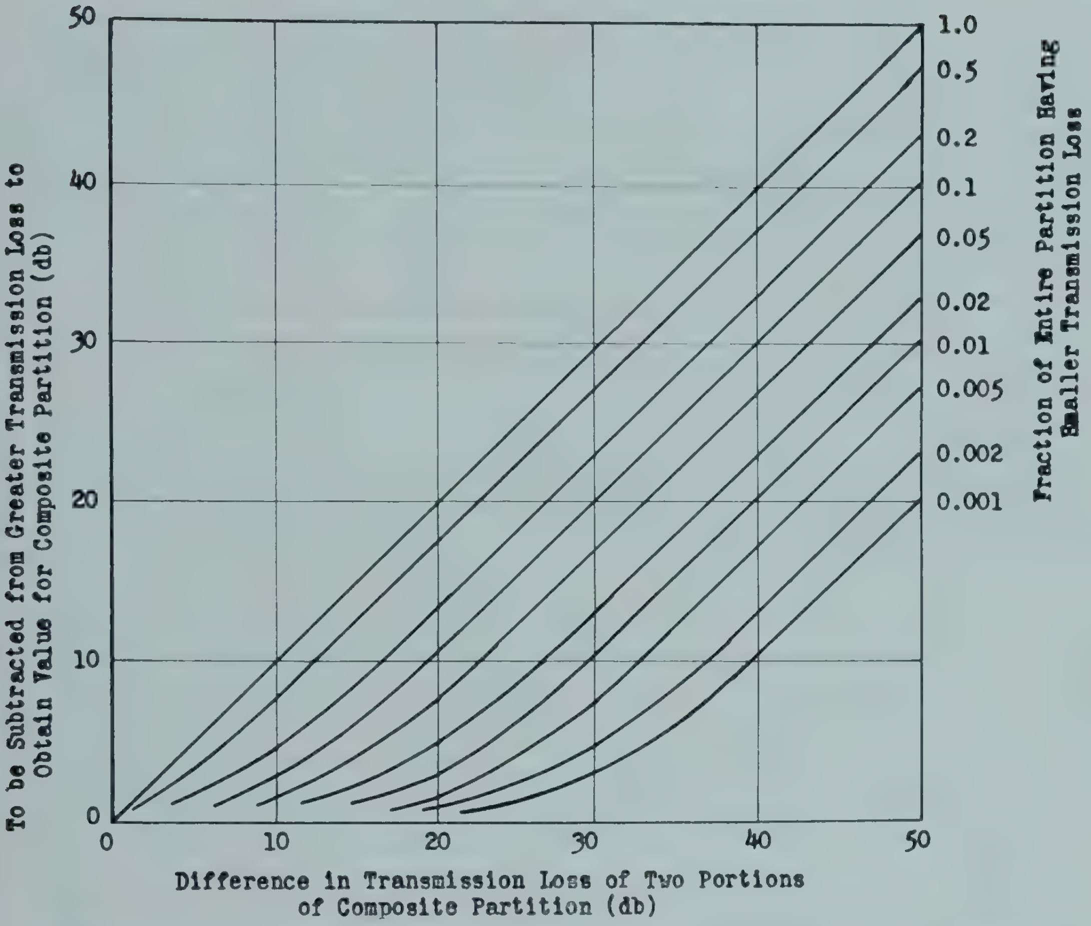

Figure 19. Curves for the calculation of the transmission loss of composite partitions.

One must always be on the alert for similar situations in construction for the purpose of noise control. Leaks around doors are extremely hard to eliminate unless great care is exercised. Poorly fitting panels and joints also are frequent sources of trouble.

J. TRANSMISSION OF SOUND FROM ONE ROOM TO ANOTHER

The curves shown in Figure 18 give the transmission loss in decibels from one side of a partition to the other. It is assumed that reflected sound is of neglible importance on the secondary side of the partition. This is not the case when the secondary side of the wall faces into a room of fairly small size with imperfectly absorbing walls. The increase in level in the secondary room resulting from reverberant sound must then be computed.

The total power radiated into the secondary room by the vibrating partition will be equal to the intensity transmitted through the wall times the surface area of the wall, S_w. In order that the sound energy in the room neither increase nor decrease, the sound power absorbed by the walls, ceiling, and floor must be exactly equal to that radiated into the room. The sound power absorbed per square foot of wall surface is equal to the incident intensity times the absorption coefficient. The total power absorbed by the walls, therefore, will be equal to the average intensity times $S\bar{\alpha}$, where S is the total surface area of the walls, ceiling, and floor and $\bar{\alpha}$ is the average absorption coefficient of the room. Equating the power absorbed by the walls to the power radiated into the room we can solve for average intensity of the reverberant sound in the room:

$$\text{Reverberant intensity} \times S\bar{\alpha} = \text{transmitted intensity} \times S_w$$

$$\text{Reverberant intensity} = \frac{S_w}{S\bar{\alpha}}(\text{transmitted intensity}) \tag{6}$$

Combining the reverberant and the transmitted sound will give the actual sound pressure in the secondary room. The difference in sound pressure levels on opposite sides of the partition is called the noise reduction and may be found with the aid of Figure 20. The horizontal axis of Figure 20 gives the ratio (S_w/S) of

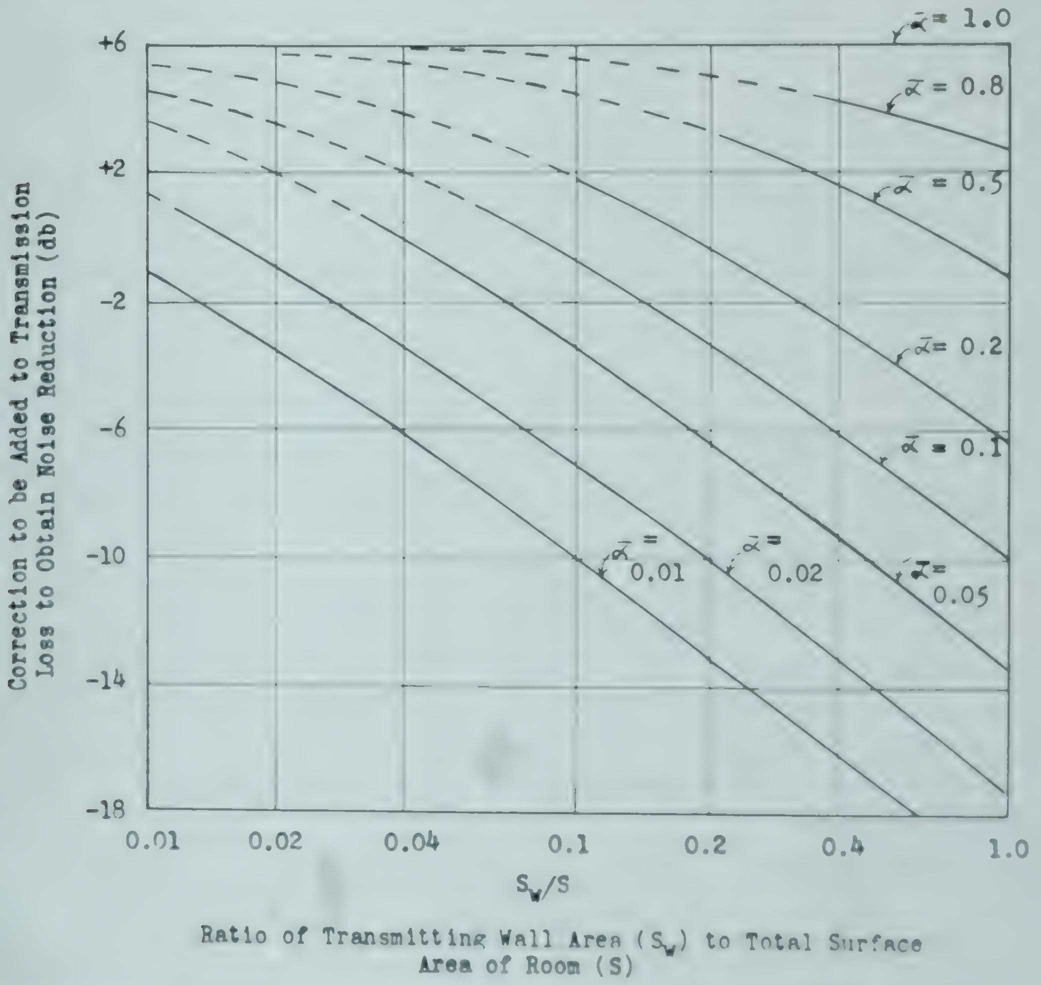

Figure 20. Curves for the calculation of the noise reduction between two rooms.

the transmitting area to the total surface area of the room. The point on the vertical axis corresponding to the intersection of the correct area ratio and the curve for the average absorption coefficient, $\bar{\alpha}$, gives the number of decibels that must be added to the transmission loss (Figure 18) to get the noise reduction.

Perfect absorption ($\bar{\alpha} = 1$) in the secondary room yields a noise reduction greater than the transmission loss. The reverberant condition in the source room causes the incident intensity level to be 6 db less than the sound pressure level (Section II.C), which gives rise to this difference. Since sound-measuring instruments react to the sound pressure rather than the sound intensity, one measures the noise reduction (difference in sound pressure level) rather than the transmission loss (difference between the incident and transmitted intensity levels).

The curves are dashed in the upper left-hand corner of Figure 20 to indicate they apply to the noise reduction measured near the partition. The levels in the remainder of the room are often less than near the partition.[10] When the radiating partition is relatively small (S_w/S small), it is often possible to use Figure 14 to find the level at locations away from the partition.

Examination of Figure 20 shows that one must have a certain amount of absorbing material in the secondary room in order to obtain the maximum benefit from an isolating partition. It should be noted, however, that there is a point of diminishing returns. It is economically wise, therefore, to add no more absorbing material than necessary to bring the level in the secondary room within a few decibels of that obtained for perfect absorption ($\bar{\alpha} = 1$).

K. A PRACTICAL EXAMPLE

Figure 21 shows a situation that lends itself to a demonstration of the use of Figures 12, 14, 18, 19, and 20. A small multislide machine that makes pins at the rate of about 300 a minute is fully automatic except for infrequent stoppages. The total sound power radiated by this machine is 80 mwatt (milliwatts), and the frequency distribution is similar to that shown for the weaving room (Figure 9). The sound power radiated in the 300 to 600 c.p.s. band is 10 mwatt. The sound pressure level in this band that exists in the right-hand room is to be computed.

First, it is convenient to replace the multislide machine by a hypothetical source radiating the same sound power, but spherical in shape and suspended in the center of the enclosure. If the area of the surface of this sphere is 1 square foot, the intensity there (at a radius $r = \sqrt{1/4\pi} = 0.28$ ft.) will be 10 mwatt per square foot. The corresponding intensity level is (see equation 3):

$$\text{Intensity level} = 10 \log_{10}\left[\frac{10}{0.1}\ 10^9\right] = 110 \text{ db}$$

The source is operating inside an enclosure in which the average absorption coefficient, $\bar{\alpha}$, of the wall is about 0.85 in the 300 to 600 c.p.s. band (Figure 12). The average distance from the center of the room to the wall is $r_0 = \sqrt{6 \times 16/4\pi} = 2.75$ feet. Figure 14 indicates that the difference between the sound pressure at the surface of the sphere $(r/r_0 = 0.28/2.75 = 0.1)$ and the wall is about 20 db. Thus, the level at the wall is 110 db — 20 db = 90 db.

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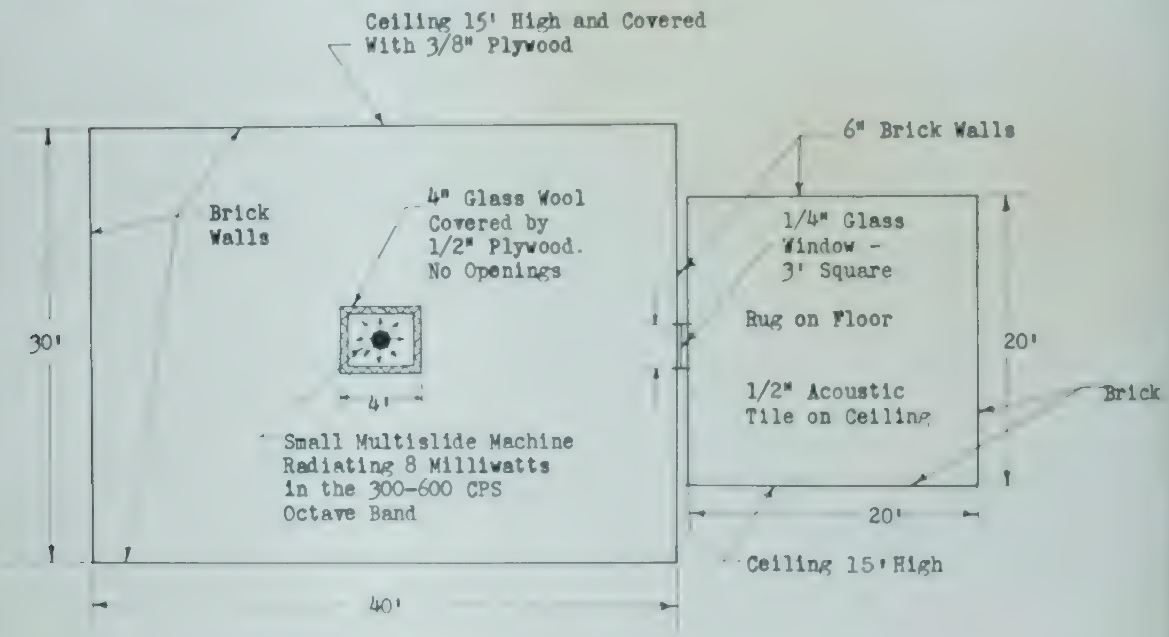
[10] L. L. Beranek, *Acoustics*. McGraw-Hill, New York, 1954.

The transmission loss through the plywood partition will be about 19 db (Figure 18) since $^1/_2$-inch thick plywood has a surface density of about 1.5 lb. per square foot (Table 4). In order to evaluate the noise reduction from the inside to the outside of this enclosure Figure 20, which requires a knowledge of S_a/S and $\bar{a}$ for the large room, must be used.



Plan of the Two Rooms Discussed in the Practical Example

Figure 21. Plan of the two rooms discussed in the practical example.

The radiating area is $S_a = 5 \times 4$ ft. $\times$ 4 ft. = 80 sq. ft., since it is assumed that the sixth side of the enclosure lies on the floor and does not radiate sound into the room. The total surface area of the large room is:

$$S = (30\text{ ft.} + 40\text{ ft.} + 30\text{ ft.} + 40\text{ ft.})\,15\text{ ft.} + (30\text{ ft.} \times 40\text{ ft.}) + (30\text{ ft.} \times 40\text{ ft.})$$
$$= 4500\text{ sq. ft.}$$

Thus, $S_a/S = 0.018$. As indicated in equation 5, the average absorption coefficient may be calculated as follows:

$$\begin{aligned}
\alpha_{\text{ceiling}}\, S_{\text{ceiling}} &= 0.12 \times 30\text{ ft.} \times 40\text{ ft.} &&= 144\\
\alpha_{\text{walls}}\, S_{\text{walls}} &= 0.03 \times 140\text{ ft.} \times 15\text{ ft.} &&= 63\\
\alpha_{\text{floor}}\, S_{\text{floor}} &= 0.03 \times 30\text{ ft.} \times 40\text{ ft.} &&= 36\\
\hline
\bar{a}S & &&= 243
\end{aligned}$$

Here, it has been assumed that the floor is concrete with an absorption coefficient equal to brick. Thus, $\bar{\alpha} = 243/4500 = 0.054$. The correction to be added to the transmission loss is approximately 2 db yielding a noise reduction of 21 db. The sound pressure level, therefore, drops from 90 db to 69 db. However, as pointed out in Section II. J, the dashed portions of the curves in Figure 20 indicate that the sound pressure may fall off as one moves away from the radiating partition. Figure 14 can be used to calculate the sound pressure level in the remainder of the room as follows.

Since the enclosure rests on the floor, the cubical source is best replaced by a hypothetical one, hemispherical in shape and of equal surface area. The radius of this hemisphere will be $r = \sqrt{80/2\pi} = 3.6$ ft. The average distance from the center of the room to the walls is $r_0 = \sqrt{4500/4\pi} = 19$ ft. Figure 14 shows that in a room with $\bar{\alpha} = 0.054$ the sound pressure level at $r/r_0 = 3.6/19 = 0.19$ is about 1 db greater than the level near the walls. Because of this very reverberant condition the sound pressure level at the partition separating the two rooms is 68 db, just 1 db less than that at the outside of the enclosure.

This partition is a 6-inch brick wall with a $^1/_4$-inch glass window occupying 9 square feet of the total area of 300 square feet. The transmission loss of the brick is about 47 db (Figure 18) based on a surface density of 66 lb. per square foot (Table 4). The transmission loss of the $^1/_4$-inch glass window is about 25 db. Since the transmission loss of the window is 22 db less than that of the wall and since the fraction of the wall occupied by the window is $9/300 = 0.03$, the transmission loss of the composite partition (Figure 19) is about 7 db less than that of the brick wall, or 40 db. In order to compute the noise reduction through this partition, we need to know the area ratio, $S_w/S = 300/2000 = 0.15$, and the average absorption coefficient, $\bar{\alpha}$:

$$\begin{array}{lll}
\alpha_{\text{ceiling}}\,S_{\text{ceiling}} & = 0.5 \times 20\text{ ft.} \times 20\text{ ft.} & = 200 \\
\alpha_{\text{walls}}\,S_{\text{walls}} & = 0.03 \times 80\text{ ft.} \times 15\text{ ft.} & = 36 \\
\alpha_{\text{floor}}\,S_{\text{floor}} & = 0.25 \times 20\text{ ft.} \times 20\text{ ft.} & = 100 \\
\hline
\bar{\alpha}S & & = 336
\end{array}$$

Thus $\bar{\alpha} = 336/2000 = 0.17$, and no correction need be added to the transmission loss (Figure 20). The noise reduction is, therefore, 40 db and the sound pressure level that exists in the room at the right in the 300 to 600 c.p.s. band is 68 db − 40 db = 28 db. A similar analysis should be performed in each of the seven other octave bands.

This example and the charts used to compute the result demonstrate some of the fundamental properties of the transmission of sound. An understanding of these properties should be of help in intelligently assessing most common noise problems. The transmission of sound through solid materials,[11] through acoustical passageways,[9,12] and through mufflers[10] are related topics and may be pursued in the literature.

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[11] C. E. Crede, *Vibration and Shock Isolation.* Wiley, New York, 1951.

III. The Ear and the Measurement of Hearing

Any discussion of industrial noise would be incomplete without a description of how it affects human beings. The physical aspects of noise can be measured in many ways, but this information would be useless without knowledge of human responses to noise. First, the operation of the auditory system will be reviewed quite briefly.

A. THE EAR

The ear may be divided into three parts called the external, middle, and inner ear (Figure 22). Sound waves enter the external ear and pass along the auditory canal, which is terminated by the ear drum membrane. This is the boundary between the external and the middle ear. Variations in the sound pressure at the drum membrane cause it to vibrate back and forth, and its displacement from normal is very nearly proportional to the sound pressure. The motion of the drum membrane is transmitted across the middle ear through a system of three small bones called the ossicles. The first of the three small bones is the malleus (hammer), which is attached to the inside of the drum membrane. The stapes (stirrup) carries the sound into the inner ear. The incus (anvil) connects the malleus to the stapes. The inner ear, or cochlea, is filled with fluid that moves

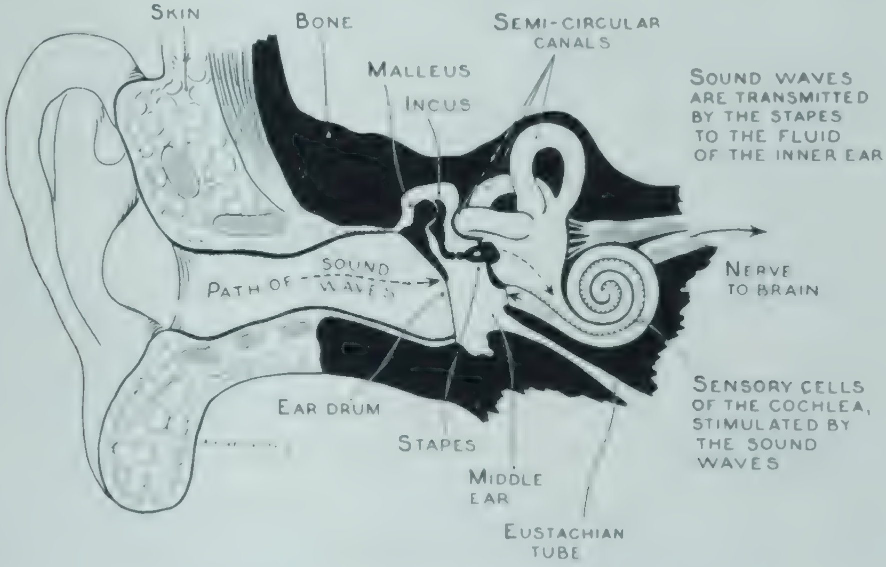
SKIN
BONE
SEMI-CIRCULAR CANALS
MALLEUS
INCUS
SOUND WAVES ARE TRANSMITTED BY THE STAPES TO THE FLUID OF THE INNER EAR
PATH OF SOUND WAVES
NERVE TO BRAIN
SENSORY CELLS OF THE COCHLEA, STIMULATED BY THE SOUND WAVES
EAR DRUM
STAPES
MIDDLE EAR
EUSTACHIAN TUBE

Figure 22. A schematic drawing of the ear.

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[9] R. H. Bolt, L. L. Beranek, and R. B. Newman, Handbook of acoustic noise control. I. Physical acoustics. Supplement 1. *Wright Air Development Center Tech. Rept.* **52-204**, Wright-Patterson Air Force Base, Ohio. 1. 1955

back and forth as a result of the vibration of the footplate of the stapes. In this manner air-pressure variations produced by the sound source are changed into motion of the ossicles by the drum membrane and then into motion of the fluid in the cochlea. Finally, the motion of the fluid excites many thousands of tiny sensory units called hair cells. After excessive exposure to intense noise, these microscopic cells may not perform properly or may even show physical damage.

The middle ear cavity, which contains the three ossicles, has an opening in the back wall that goes to the mastoid area behind the ear, and an opening in the front wall that connects by way of a tube with the back of the nose above the soft palate. This connection is called the Eustachian tube, and one of its functions is to equalize the atmospheric pressure on the opposite sides of the drum membrane.

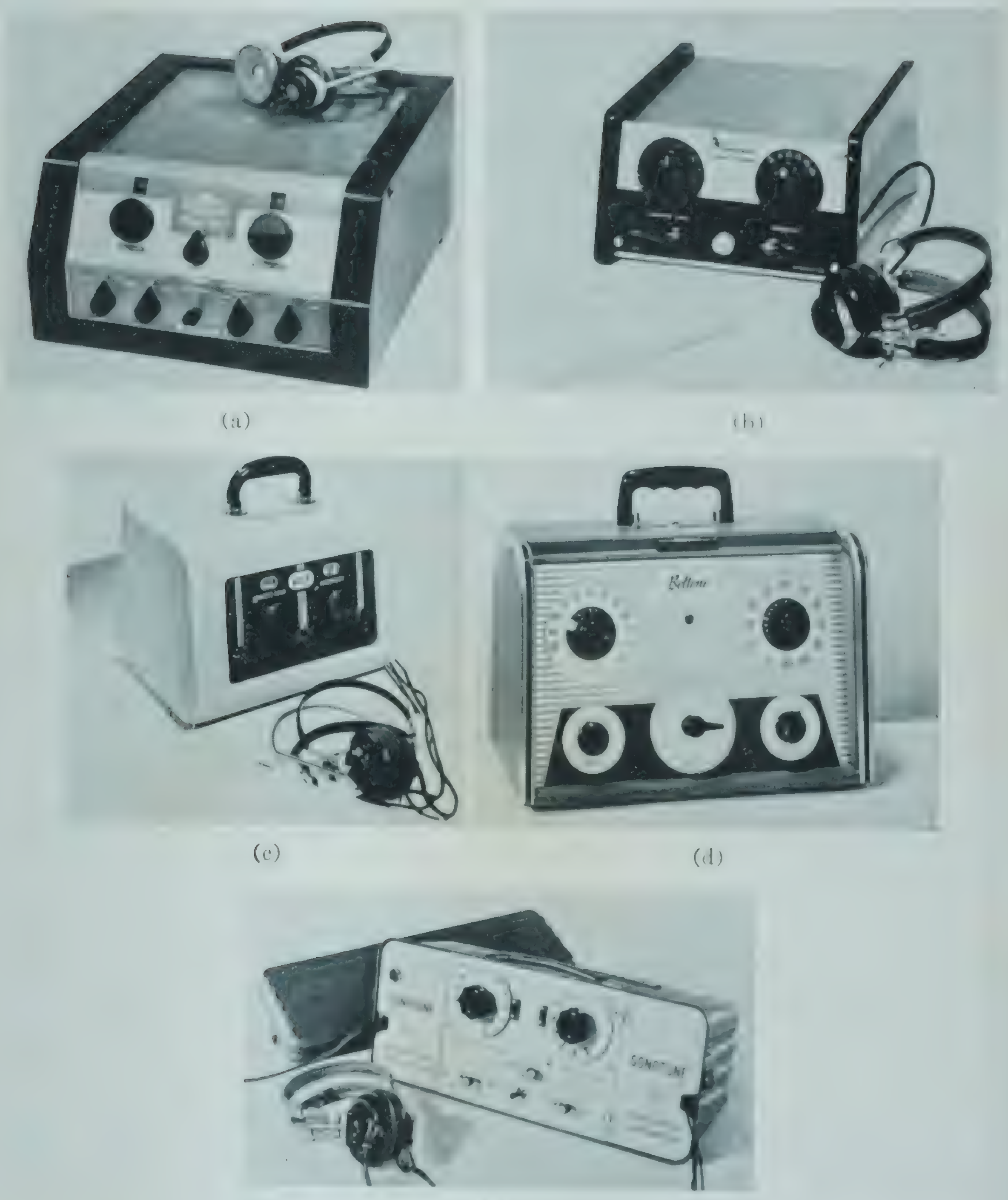
The cochlea is a spiral channel in the skull. It may be visualized as a tube divided lengthwise into three compartments, all filled with fluid. The wall separating two of the compartments is called the cochlear partition, and embedded in it are about 20,000 hair cells that serve to transform the mechanical motion into electrical signals. Nerve endings located at the base of the hair cells are stimulated by these electrical signals and initiate neural impulses that travel along the auditory nerve to higher nervous centers.

The hair cells nearest the middle ear are stimulated most effectively by sounds containing the highest audible frequencies. Sounds with low frequency components stimulate most effectively the hair cells in the area near the tip of the cochlea and farthest from the middle ear. The extremes of the audible frequency range are not sharply defined, but are related to the intensity of the sound. In young normal ears these extremes are approximately 30 and 15,000 c.p.s. for intensities which in the middle frequency range would correspond to that of the ordinary speaking voice. At greater intensities many listeners can hear sounds from 20 to 20,000 c.p.s.

Since the cochlea is set in the skull, intense vibration of the head at audible frequencies will agitate the fluid in the cochlea and cause the sensation of sound. This process is called hearing by "bone conduction." By contrast, the usual method, utilizing the drum membrane and ossicles, is called hearing by "air conduction."

B. THE MEASUREMENT OF HEARING

The device used today to measure hearing is called an audiometer. Years ago tuning forks, watch ticks, coin clicks, whispers, and voice tests were used exclusively. With the advent of the vacuum tube more exact methods of measurement became available. In the early 1930's the electronic audiometer developed rapidly and soon reached a state closely resembling today's models. The photographs in Figure 23 show five of the commercially available models that have been designed to meet the specifications of the American Standards Association and the American Medical Association. Those shown are adequate for most in-



(a) (b)

(c) (d)

(e)

Figure 23. Air-conduction, pure-tone audiometers that can be used in industrial hearing conservation programs. (Courtesy Audivox, Inc. (a), U. S. Recording Co. (b), Audiometer Sales Corp. (c), Beltone Hearing Aid Co. (d), and Sonotone Corp. (e).)

dustrial applications, but more complete models are available for diagnostic purposes. Attached to each audiometer is a set of earphones fitted with rubber cushions for a snug fit over the ears. An electrical signal produced by the audiometer is transmitted to the earphones where it is converted to an acoustic signal.

Industrial programs for the conservation of hearing require knowledge of only the simplest aspects of audiometry. The following discussion is limited to these basic aspects, but this should not lead the reader to the conclusion that the measurement of hearing is an uncomplicated field. On the contrary, the diagnosis of the cause and nature of a hearing impairment by an otologist may involve the results of a dozen tests not described here and, in addition, may require careful judgment based on years of medical experience.

C. THRESHOLD OF HEARING

A sound is at the threshold of hearing when it is just intense enough to evoke a response from the listener. Since a listener's threshold may vary slightly from moment to moment, the average of the responses to a number of trials is usually obtained. To describe a threshold completely one must report the nature of the sound, the physical measurements made to specify the sound, and, in addition, the exact nature of the response or series of responses that the listener makes.

Many different sounds have been used in threshold measurements. Pure tones, speech, and noise are the major classifications of useful sounds, but each group may be subdivided many times. For instance, the pure tone may be presented at any frequency in the audible range, may be interrupted or steady, and may have a gradual or an abrupt beginning. The speech material may be sentences, words, or syllables. Noise may be presented with a vast variety of spectra and band widths. Only thresholds obtained with the same kind of sounds can be expected to be the same.

For most audiometric measurements the sound is specified in terms of the sound pressure level that the earphone of the audiometer produces in a small cavity whose volume is about the same as that of the outer ear when closed by the earphone. The sound pressure produced in this cavity is, throughout the middle frequency range, very nearly that produced in the ear canal when it is covered by the same earphone.

The exact nature of the response elicited from the listener is often less carefully specified. In measurements of the threshold of intelligibility for speech the response requested may be that the listener repeat words he has heard. In measurements of the threshold of detectability the response that may be requested is a signal from the listener at the instant that the sound becomes audible as the sound pressure is increased. Another response that may be requested is a signal from the listener at the instant the sound becomes inaudible as the sound pressure is decreased. Usually these two responses give slightly different thresholds. Averaging the results of a number of threshold determinations by each of these two methods is usually considered good audiometric procedure.

Thus, the method for measurement of the sound pressure, the kind of response that the listener is requested to give and, of course, the nature and manner of presentation of the sound are all factors that can influence the threshold of hearing. Therefore, one must use standard audiometric techniques and make direct comparisons of thresholds only under like circumstances.

D. NORMAL HEARING

Normal hearing is the threshold of hearing found in young people with no evidence or history of infection or other diseases of the ears. As with height or weight, their thresholds of hearing are not all the same, but are distributed over a range of sound pressure levels of about 25 db. This is the "range of normal hearing."[13] The thresholds of these young people are distributed throughout this range in a nonuniform manner, as are their heights and weights. Many are near the center of the range and only a few are at the extremes.

For convenience in comparing thresholds of hearing sensitivity, a decibel scale is used. The reference level for most hearing scales is set arbitrarily at the *commonest* (modal) threshold sound pressure level (not the *lowest* sound pressure level) for a group of listeners with normal hearing. The difference between this arbitrary reference level and the sound pressure level at the listener's threshold is called his "hearing loss." The use of the word "loss" here may be somewhat misleading because the smaller "hearing losses" lie within the "range of normal hearing."

Another common cause of confusion is the existence of "negative hearing losses." Since the reference level is the *commonest* threshold for normal listeners, there will be many whose threshold sound pressure level is less than the reference level. Thus listeners with "negative hearing losses" should be expected when any group of normal listeners are tested, under appropriate conditions.

Because "hearing loss" is a term reserved for a particular use, it should not be applied to the amount of hearing lost by an individual between two audiometric examinations. Such changes in an individual's hearing are called "threshold shifts." For example, a man has a 30 db "hearing loss" as the result of a "threshold shift" of 20 db. His original 10 db "hearing loss" may have been quite normal for *him* contrary to the misleading implication of the words "hearing loss."

E. PURE-TONE AUDIOMETRY

The instrument of choice in hearing-conservation programs is the air-conduction, pure-tone audiometer. This device presents a tone like that from a tuning fork to the ear of the listener. The hearing loss for pure tones is usually determined at a number of frequencies, and a graph of hearing loss vs. frequency is called an audiogram (Figure 24). Note that reductions in hearing sensitivity, hearing losses, are plotted downward. Negative hearing losses are plotted upward, above the reference level indicated by the double line.

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[13] For a clear statement of the concept "range of normal hearing," see Council on Physical Medicine and Rehabilitation, Principles for evaluating hearing loss, *J. Am. Med. Assoc.*, **157**, 1408 (1955).

The dial of the audiometer that controls the intensity of the tone presented to the listener's ear is called the hearing-loss dial. The 0 db setting of this dial corresponds to a reference level for the threshold for pure tones that was derived from the commonest value of the thresholds of a large number of listeners with presumably normal ears measured in a survey carried out by the United States Public Health Service in 1935.[14] It should be emphasized that the reference level does not represent the best human hearing, nor the boundary between normal and abnormal hearing. The reference level does represent a threshold that is a few decibels more sensitive than a threshold in the middle of the "range of normal hearing."

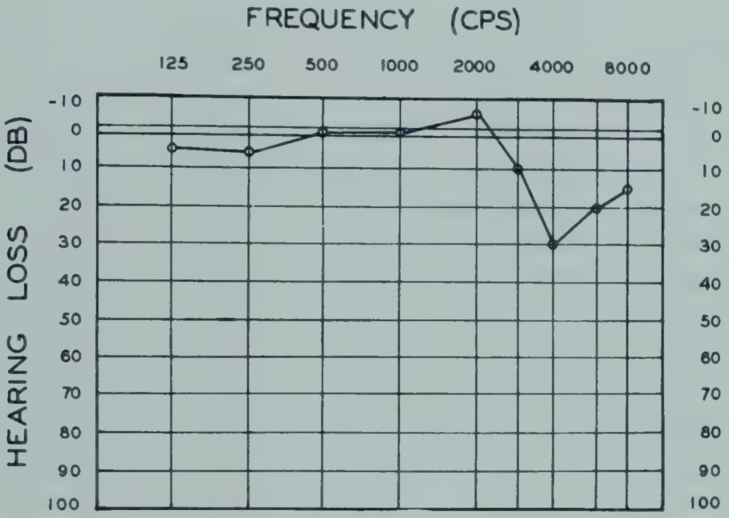

Figure 24. The audiogram, a method for recording audiometric data.

On most audiometers, the markings on the hearing-loss dial extend from —10 db (an extremely faint tone) to 100 db (a very intense tone). The "range of normal" extends from —10 db to about +15 db, but the limits are not clearly defined. It is important to note that these values of hearing loss do not correspond to either sound pressure levels or intensity levels even though the units are decibels. This is because the reference for the hearing-loss scale is different from that for either of the two level scales and, in fact, varies from frequency to frequency as shown in Table 5.

A second major control on the audiometer is the frequency dial, which allows the operator to switch to any one of a group of test tones. Those required on

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[14] National Health Survey: 1935–1936, Normal hearing by air and bone conduction, *National Health Survey, Prelim. Rept. Hearing Study Series, Bull.* **5,** 1 (1938).

TABLE 5

Frequency (c.p.s.)	Reference pressure for sound pressure level (μbar)	Reference pressure for hearing loss[a] (μbar)	Sound pressure level[a] corresponding to 0 db hearing loss (db)
125	.0002	.106	54.5
250	.0002	.0191	39.6
500	.0002	.00347	24.8
1000	.0002	.00137	16.7
2000	.0002	.00141	17.0
4000	.0002	.00114	15.1
8000	.0002	.00221	20.9

[a] These pressures are those that should be produced by a Western Electric 705-A earphone measured in a coupler built and used according to the specifications set forth in American Standard for Audiometers for General Diagnostic Purposes.[15]

audiometers designed for diagnostic purposes are 125, 250, 500, 1000, 2000, 4000, and 8000 c.p.s.[15] For industrial programs a so-called "screening audiometer" having only four test frequencies, 500, 1000, 2000, and 4000 c.p.s., may be used.[16] Many of the "screening audiometers" being produced today have additional test frequencies at 3000 and 6000 c.p.s. because these test tones are very useful in industrial hearing conservation programs.

In general, the test frequencies are related in a simple manner. Each successive tone is an octave (a multiple of 2) above the previous tone. This rule also may be applied to the series of test tones that were originally used on audiometers. A frequency of 256 c.p.s., which is almost equal to that of middle C on the piano, was used instead of 250 c.p.s. The remaining test tones of the older sequence were 128, 512, 1024, 2048, 4096, and 8192 c.p.s. The slight differences from the present frequency series are, for all practical purposes, unimportant.

F. SOUND INTENSITY PRODUCED BY THE EARPHONES

The intensity of a tone produced in the ear of the person being tested will not always be indicated exactly by the setting of the hearing-loss dial. At low frequencies any air leak around the cushion of the earphone will be very important in determining the intensity of the tone actually produced in the ear canal. Since these leaks cannot be completely eliminated with present cushions, there is a significant amount of uncertainty in audiometer measurements at frequencies of 250 c.p.s. and below. The lower the frequency, the less meaningful the setting of the hearing-loss dial becomes. At 250 c.p.s. the range of variation in the intensity of the tone produced is about 15 db, and at 125 c.p.s. the range of variation may be as much as 20 db. There are similar limitations on the high-frequency test tones produced by the earphones. Their exact placement on the ear and the shape and size of the ear canal will cause variations in the sound intensity produced. Also the problems involved in the calibration of an earphone become more serious at these frequencies. The range of variation in the intensity of the tone produced is 10 db at 4000 c.p.s. and is considerably greater at 8000 c.p.s. and higher.

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[15] American Standard for Audiometers for General Diagnostic Purposes, Z24.5-1951. American Standards Association, New York, 1951.

With reasonable care hearing measurements at 500 to 2000 c.p.s. inclusive should be reliable within a range of 5 db on all except the most unusual ears. At both higher and lower frequencies the intensity generated in the ear canal for a given setting of the hearing-loss dial may be significantly different from person to person. These differences should be borne in mind when audiometer measurements at extreme frequencies are undertaken.

Neither the electronic components of the audiometer itself nor the earphones remain absolutely stable. Over long periods of time, changes may be observed in the sound intensity produced by the earphones for given settings of the hearing-loss and frequency dials. In recent years, however, the seriousness of this problem has been greatly reduced by advances in electronic and earphone design. It is still necessary, nevertheless, to maintain some sort of check on the calibration of the entire system. Otherwise one can never be sure that the sound intensity produced by the earphones corresponds as closely as it should to that indicated by the hearing-loss dial.

G. PHYSICAL METHODS OF CALIBRATION

The physical method for calibration of the audiometer utilizes a microphone and a small cavity, both of which are described in detail in recent American Standards.[15,16] The earphone is placed on the cavity and the intensity generated within is measured by the microphone. The sound pressure level that should be generated by a Western Electric 705-A earphone at each of the test frequencies for 0 db setting of the hearing-loss dial is given in Table 5. Similar requirements for other earphones are given in American Standard Specification for Pure-Tone Audiometers for Screening Purposes.[16]

Audiometers are calibrated routinely by this method by the manufacturer, but for others it is usually a complex and expensive procedure. An experienced acoustical engineer can accomplish these measurements without error, but others may have difficulty. Therefore, it seems clear that most audiometers will not have the benefit of frequent calibration by physical methods. Most organizations have neither the necessary funds nor personnel.

The electrical portion of the audiometer can be checked by simpler measurements. Upon receipt of a new audiometer the voltage at both earphones is measured accurately and recorded for each test frequency. Periodically this test can be repeated to determine if any electrical changes have taken place. Deviations of more than ±2 db indicate that the instrument is in need of repair.

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[16] American Standard Specification for Pure-Tone Audiometers for Screening Purposes, Z24.12-1952. American Standards Association, New York, 1952.

Changes in the sensitivity of the earphones cannot, of course, be detected by this method.

H. PSYCHOPHYSICAL METHODS OF CALIBRATION

A useful method for the calibration of the entire audiometer involves the measurement of the hearing of a number of individuals who have no history of noise exposure or other hearing difficulties (see Section III.O). The average audiogram of this group will usually give a reliable indication of the calibration of the audiometer.

The audiometric procedure for the test group should be the same as the standard procedure adopted for all tests (see, for instance, Hirsh[17]). About 10 young people should be tested in both ears. This number of audiograms appears to be sufficiently large to give a reliable average at the important audiometric frequencies, 500, 1000, 2000, and 4000 c.p.s. If measurements at either higher or lower frequencies are contemplated, it may be necessary to test a larger group of people. If the average of the audiograms at the important frequencies is within 5 db of the zero setting, it may be assumed that the audiometer is calibrated correctly. If larger deviations are observed and it is reasonably certain that the group used in the test is normal, the instrument should be returned to the manufacturer or his representative for repair and recalibration. If the normalcy of the test group is subject to question, comparison measurements can be made on another audiometer.

A simpler psychophysical procedure may be used to detect changes in the calibration of the audiometer. A small group of practiced listeners (perhaps 4 or 5) should be tested regularly. Any systematic change in their thresholds is usually an indication of a change in the calibration. Of course, the operator should be suspicious of individual threshold shifts. They may be caused by wax in the ear canal or a mild respiratory infection. Since this procedure does not attempt to give an absolute calibration of the instrument, the listeners need not be young nor have normal hearing provided that their hearing loss is relatively stable. Because this procedure is quite simple to carry out, it is recommended that it be repeated with the same listeners at least once for each full week of operation of the audiometer.

I. MASKING

Acuity of hearing is influenced strongly by the ambient noise in the testing room. If this ambient or background noise is excessive, the quiet tones cannot be heard and the individual will show an apparent hearing loss. This apparent hearing loss is the result of an auditory phenomenon called masking. We are familiar with other aspects of this phenomenon, such as the difficulty in hearing our automobile radios as a result of road or wind noise. Masking means the inability to hear a desired signal in the presence of an undesired sound or background noise. In the measurement of hearing, background noise will reduce the ability of the subject to hear the test signal and, therefore, produce an apparent hearing loss.

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[17] I. J. Hirsh, *The Measurement of Hearing*. McGraw-Hill, New York, 1953, p. 364.

J. HOW QUIET MUST IT BE TO MEASURE NORMAL HEARING?

In order to design satisfactory yet practical rooms for the pure-tone testing of hearing we should know the allowable background noise level for each of the audiometric test tones. The noise at frequencies near that of a test tone is most effective in masking that tone and, therefore, the criteria for the background noise in an audiometer room will depend directly on the test frequencies that are to be used in the hearing measurements. For example, only the criterion shown in Table 6 for the 300 to 600 c.p.s. octave band need be observed if correct audiometric measurements are to be made at 500 c.p.s. The appropriate octave band criteria for other audiometric test frequencies are also listed in Table 6. If the octave band levels of the background noise in the test room exceed any of these criteria, masking of the corresponding test tones is likely for a 0 db setting of the hearing-loss dial. This condition would cause some listeners to have an apparent hearing loss that would disappear were the measurement made in a room with background noise less than that specified in Table 6.

TABLE 6

Maximum Allowable Sound Pressure Levels for No Masking at Zero Hearing Loss on Standard Audiometers

Audiometric test frequency (c.p.s.)	Important octave band (c.p.s.)	Sound pressure level in the octave band (db)
500	300–600	40
1000	600–1200	40
2000	1200–2400	47
4000	2400–4800	57

It should be clearly understood that there is no relation whatsoever between an audiogram measured in the presence of excessive background noise and the true audiogram measured in quiet. It is *not* possible to apply a correction to measurements made in the presence of excessive noise. If useful audiometric records are to be kept, it is mandatory that the measurements be made in a sufficiently quiet environment.

K. GENERAL PRINCIPLES OF AUDIOMETER ROOM DESIGN

The background noise in an audiometer room is usually most intense at low frequencies. The control of low frequency noise is particularly difficult. Small leaks around doors and windows and the openings of ventilating systems provide excellent paths for the transmission of these sounds. Vibrations travelling through a building often manifest themselves as a low frequency rumble. Reduction of the low frequency noise will usually make the room sufficiently quiet for hearing measurements.

Methods for reducing the level of the low frequency noise, in the order of their effectiveness, are: *(1)* the construction of an acoustically isolated room within, but not solidly connected to, the original room; *(2)* acoustical treatment of the inside of ventilating ductwork opening into the room, including removal of noisy ventilating grills and diffusers; *(3)* adequate sealing of all doors and other openings into the room; and *(4)* use of acoustical material on walls, floor, and ceiling.

Rugs and acoustical material will reduce the noise in the high- and mid-frequency range, but will have only a slight effect on low frequencies. These materials are useful, however, in reducing the level of noises generated within the room. Therefore, it is wise to lay a thick carpet and install acoustical tile on the ceiling and walls.

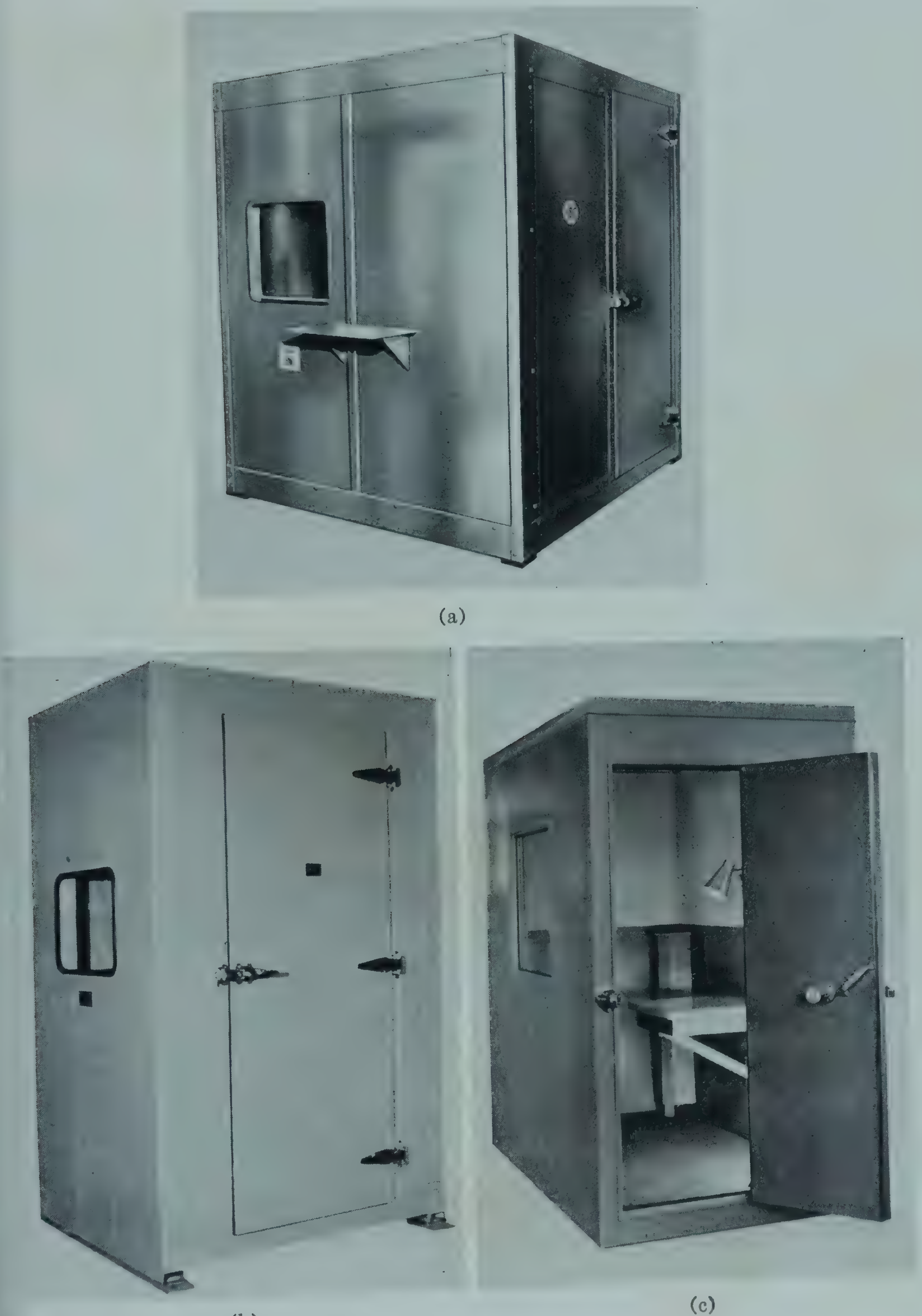
The room should be about 6 feet square if both the tester and the listener are to be inside simultaneously. Steady ventilation is necessary if the room is to be used in hot weather. Earphone and 110-volt connections should be brought through the wall with care to insure that no sound can leak through or around the conduit or cable. If a window is provided, it is possible to have the tester outside, and a room smaller than 6 feet square is practical. Prefabricated rooms are available and three examples of designs embodying most of these principles are shown in Figure 25.

L. SPEECH AUDIOMETRY

Speech audiometry holds great promise as a method of determining, in a realistic manner, disability resulting from a hearing impairment. Unfortunately, it yields little information about the cause, nor can it detect the small changes that usually foreshadow any significant permanent hearing impairment.

Instead of presenting pure tones to the listener, the speech audiometer reproduces certain standard lists of syllables, words, or sentences. This may be accomplished by either disc or tape recording. The sound pressure level at which the speech sounds are presented to the listener is controlled by a dial similar to the hearing-loss dial on the pure-tone audiometer. The sound pressure level at which the listener correctly repeats just half of the material presented is called the threshold of hearing for speech. The threshold will depend on the material presented, so that a different reference level equivalent to no "hearing loss" must be established experimentally for each recording.

Many kinds of speech material have been used for threshold measurements. Some have been widely used, and their reliability is well established. Others have had only limited use, which makes the comparison of results from different testing facilities difficult. None of the well-validated tests contain speech material typical of that which the average person is called upon to interpret in his daily living. It is



(a)

(b)

(c)

Figure 25. Three commercial audiometric booths. (Courtesy Industrial Sound Control Inc. (a), Industrial Acoustics Co., Inc. (b), and Burgess-Manning Co. (c).)

anticipated that in the near future, however, standardized selections of everyday speech will be available. This will greatly enhance the usefulness to industry of the speech audiometer, since by measuring the threshold of hearing for everyday speech, it is possible to make some estimate of the listener's practical ability to hear correctly everyday speech.

M. RELATION BETWEEN THE THRESHOLDS FOR PURE TONES AND SPEECH

Because of the complications introduced by the variety of causes of hearing loss and by the variations in the shape of the audiogram, there is no method that precisely predicts an individual's "hearing for speech" directly from his pure-tone audiogram. In addition, different kinds of speech tests rank hearing impairments differently. Therefore, it is impossible to make this computation with accuracy for each individual. However, a simple rule may be used to obtain the relation that most often holds between the thresholds for pure tones and speech. The lack of ability to hear speech at threshold is highly correlated with the average of the pure-tone hearing losses at 500, 1000, and 2000 c.p.s.[18] Thus, the hearing losses in decibels at these three frequencies are added and the total divided by 3 to get an estimated "hearing loss for speech."

The fact that only the three frequencies 500, 1000, and 2000 c.p.s. are used in this computation does not necessarily mean that sounds above 2000 c.p.s. are unimportant in the understanding of speech. It is the high correlation between this average of the three pure-tone hearing losses and the "hearing loss for speech" that allows us to bypass the details of the very complicated matter of how we understand speech.

N. AUDIOMETRIC PROGRAMS

It is extremely important that industrial audiometric programs be under the supervision of a competent otologist whenever one is available. Many matters may arise that require his medical judgment, and his testimony about the quality of the audiometric program may be extremely valuable in any future litigation.

The training of the personnel who actually carry out the audiometric program should be approved or supervised by the otologist. Such personnel may include a technician, a nurse, an audiologist, or the plant physician. A mutually satisfactory audiometric procedure should be developed and followed rigorously. Procedures should be set up for the proper care of those whose audiograms indicate unusual susceptibility to noise or those who show symptoms of any of the many other kinds of hearing impairment. Advice about audiometric programs may be obtained from the Subcommittee on Noise in Industry of the Committee on the

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[18] R. Carhart, Speech reception in relation to pattern of pure-tone loss, *J. Speech Disorders,* **11**, 97 (1946).

Conservation of Hearing of the American Academy of Ophthalmology and Otolaryngology.[19]

O. HEARING IMPAIRMENT

There are many disorders that can affect the hearing apparatus. Traditionally these disorders are grouped according to whether they occur in the sound-conducting apparatus (outer and middle ear) or in the remainder of the system (cochlea, auditory nerve, and central nervous system). The former group are called conductive disorders and the latter have variously been called perceptive, nerve, or inner-ear disorders. In order to emphasize the different character and the importance of disorders of the central nervous system, this group has been listed separately in Table 7.

TABLE 7

Hearing Impairments and Their Causes

I. Disorders of the sound-conducting apparatus.
   A. Obstruction of the ear canal by:
      1. Excess wax or foreign bodies.
      2. Swelling from bacterial or fungus infection, particularly in hot, wet climates.
   B. Movement of the drum membrane and the ossicular chain hindered by:
      1. Extreme displacement of the drum membrane and the ligaments of the ossicular chain caused by barometric changes that occur when the Eustachian tube is closed (swelling from an adenoid infection or a cold may produce closure).
      2. Fluid or pus in the middle ear.
      3. Bands of scarlike, fibrous tissue called "adhesions" that tend to increase in number and size as a result of repeated middle ear infections.
      4. Otosclerosis, an abnormal bonelike growth on the stapes that begins just after adolescence and becomes progressively worse.
   C. Damage to drum membrane or ossicular chain as a result of:
      1. Explosion or a blow on the head.
      2. Chronic infection.
      3. Removal by a surgeon to halt the spread of infection.
II. Disorders of the auditory receiving apparatus.
   A. Malfunctioning of the cochlea as a result of:
      1. Ménière's disease, a transient disorder that is usually characterized by attacks of dizziness, ringing in the ears, and loss of the ability to understand words even when sounds are heard.
      2. Hereditary causes that produce a permanent and sometimes progressive hearing loss.

(continued)

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[19] Inquiries may be sent to the Director of Research, Subcommittee on Noise in Industry, 111 N. Bonnie Brae, Los Angeles, Calif. In addition to providing advice to industry on audiometric programs, the Subcommittee acts as a central agency for the collection and analysis of data relating hearing loss to noise exposure. This work is directed toward increasing knowledge of the effects of noise. Groups interested in contributing audiometric data should write to the Subcommittee for information on recommended procedures and standardized cards for collecting data.

TABLE 7 (*continued*)

3. Infectious diseases, such as mumps and meningitis, that usually occur during childhood.
4. Heavy dosage of certain drugs, particularly quinine, but individual susceptibility varies widely.
5. Mechanical damage from a blow on the head or an explosion.
6. Presbycusis, a permanent and progressive degeneration of the hair cells and/or nerve endings that normally accompanies advancing age.
7. Exposure to intense noise (see Section III.P).

B. Lesions of the auditory nerve, usually caused by tumors.

III. Disorders of the central nervous system.

A. Organic changes that may accompany:
1. Advancing age, including effects of arteriosclerosis.
2. A skull fracture, penetration wound, brain tumors, multiple sclerosis, and cerebral palsy.

B. Nonorganic disturbances:
1. Psychogenic deafness, a kind of hearing loss that cannot be shown to involve any organic disorder and often may yield to psychiatric treatment.
2. Malingering, the willful feigning of a hearing loss for gain, usually monetary.

Any such listing will be complicated by certain boundary-line disorders and cases of so-called "mixed" hearing impairment that cannot properly be placed entirely in one group. The table is not a complete catalogue, but most impairments important in adults are included. Disorders that may be present in the newborn infant are omitted because they are of little importance in the working population. For example, congenital malformation of any part of the auditory apparatus may be present at birth. Such disorders do not complicate industrial hearing conservation programs.

The diagnosis and specification of the cause of the disorder become, in general, more difficult in the groups headed "Receiving Apparatus" and "Central Nervous System." For many of these disorders the characteristics are not specific and the cause is incompletely known.

P. CHARACTERISTICS OF HEARING LOSS RESULTING FROM NOISE

Early losses in hearing sensitivity resulting from most industrial noise exposures ordinarily are not recognized by the individual and can be detected only by pure-tone audiometry. This is because the initial hearing loss is usually in the frequency range between 3000 and 6000 c.p.s. and does not noticeably affect the hearing for speech. As the impairment increases because of continued exposure to intense noise, losses begin to appear at 2000, 1000, and finally 500 c.p.s. When the hearing loss at these frequencies is sufficiently great, a reduction in the hearing for speech at conversational intensities is noted.

Hearing loss beyond the "range of normal" in an individual exposed to noise may represent a permanent hearing loss, but a certain amount of hearing sensitivity is often recovered when the individual is removed from the noise environment. Most of the improvement in the threshold will occur within a short time (probably less than a week) after removal from the noise.

There is good evidence to indicate that these shifts in the threshold of hearing are most obvious during the first year or so of noise exposure. A person who has not been in a noisy environment for long usually will show considerable improvement in his hearing following removal from the noise. Those with considerable hearing loss resulting from many years of noise exposure are likely to show only slight improvement.

There are two major pathways that conduct sound to the inner ear, the normal pathway and a bone pathway that circumvents the ear canal, the drum membrane, and the ossicles. Hearing by "bone conduction" through the skull is much less sensitive than hearing in the normal manner by "air conduction." A comparison of the bone- and air-conduction thresholds will often yield important diagnostic information about the condition of the conducting apparatus. For instance, a hearing loss by air conduction coupled with no hearing loss by bone conduction indicates a malfunctioning of either the external or middle ear, but not the inner ear. On the other hand, a person with a significant noise-induced hearing impairment will have a hearing loss by bone conduction as well as by air conduction.

Q. RELATIONS OF HEARING IMPAIRMENT TO NOISE EXPOSURE

Prolonged exposure to intense noise may cause a hearing impairment. The known data relating hearing loss to noise exposure are described in detail in a report by the American Standards Association.[20] Although insufficient data are available on exposure to noise that is either extremely intense, produced by impact, or intermittent in nature, it is possible in other instances to make an estimate of the average of the pure-tone hearing losses that a group of workers may be expected to incur.

As yet there are insufficient data to describe properly the distribution of individual noise-induced hearing losses about the average for a given noise exposure. However, the susceptibility to noise clearly varies widely from individual to individual. Some severe noise exposures can cause either a negligible hearing impairment or almost complete deafness in an individual, depending upon whether he is highly susceptible or very resistant to impairment by noise.

Even if the information relating a noise exposure to the distribution of hearing impairments that it may produce were complete, it still would be impossible, without additional information, to estimate the practical seriousness of a noise exposure. The missing information is the relation between a man's pure-tone hearing loss and his disability resulting from the hearing loss. The number of people who can claim compensation for their hearing disability and the magnitude of their claims will depend upon which of the several methods of computation are used to bridge this gap in information. It seems certain that eventually there will be standardization in this area, and it is probable that a method relating compensation to the lack of ability to understand everyday speech will be agreed upon

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[20] The Relations of Hearing Loss to Noise Exposure, Z24-X2, American Standards Association, New York, 1954.

R. THE SEVERITY OF A NOISE EXPOSURE

The severity of a noise exposure depends upon a number of factors. In assessing any noise exposure, each of these factors should be evaluated as carefully as possible.

The *intensity level* of the noise is probably the most important single factor in determining the severity of the exposure, but by itself can never be used as a criterion for safety or as evidence of a causal relationship between a noise and a person's hearing impairment. For instance, peak sound pressures up to 0.03 bar (a pure tone with a level of 160 db would have the same peak pressure) can be tolerated without permanent damage to the hearing apparatus under circumstances such as short exposures to artillery fire and heavy explosions.[21]

The *duration of a noise exposure* is a tremendously important factor. The longer the exposure to intense noise, the greater and more permanent can be the resulting impairment. An exposure that continues for eight hours a day throughout a working lifetime is many times more serious than one of similar intensity that occurs only once and lasts for a few minutes.

The *temporal pattern* of the noise must be taken into consideration. Exposure to a noise for one hour out of eight per day may have a completely different effect than exposure to the same noise for one minute out of every eight throughout the day. Impact noises, such as those produced by drop hammers, are momentarily of very high intensity, yet the average intensity may be relatively low. Present data give us almost no information that allows comparison of the effects of these intermittent noises with the somewhat better-known effects of continuous noise.

The *frequency distribution* of the noise must be examined because damage to the hair cells is not uniformly probable nor is it equally significant throughout the audible frequency range. Hearing loss occurs at other frequencies than those present in the stimulating noise. In fact, no matter what the spectrum of the noise, the irreversible part of the hearing loss is usually most severe in the 3000 to 6000 c.p.s. range. However, when the energy of the stimulating noise is primarily in the mid-frequency range, there is likely to be more hearing loss below 3000 c.p.s. than when the energy of the stimulating noise is primarily in the high frequency range. Since hearing loss at high frequencies has little effect on the ability to understand everyday speech, noise concentrated in the mid-frequency range is a more important hazard than a noise of similar intensity at high frequencies.

Hearing loss is relatively less probable when the stimulating noise is concentrated at low frequencies. Thus the mid-frequency range (300 to 2400 c.p.s.) is of supreme importance in noise control for the conservation of hearing. In fact, present data[20] indicate that the 300 to 600 c.p.s. octave band should be weighted most heavily in estimating the effects of noise on the hearing loss for speech.

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[21] BENOX Report, An exploratory study of the biological effects of noise, *ONR Project* **NR 144079**, 1953, p. 32.

The band width of the noise should be known, at least approximately. Narrow-band and pure-tone sounds appear to be somewhat more damaging than wide-band noises of the same intensity.

The *susceptibility to noise* of exposed persons may vary over a wide range. Some fail to develop a significant hearing loss after long exposure to intense noise, whereas others may develop a severe impairment. The unusually susceptible individual can be tentatively identified only through repeated audiograms taken on the exposed group. He will suffer significantly greater changes in hearing sensitivity than his co-workers in the same noise exposure. Also, upon leaving the noise he is less likely to show rapid improvement in his hearing.

8. HOW MUCH NOISE EXPOSURE CAUSES HEARING DISABILITY?

The variations in individual susceptibility make the task of answering the question "How much noise is too much?" extremely difficult. A small percentage of any group of people will incur hearing loss from age and other causes no matter what their noise environment. Some will incur presbycusis (the natural loss of hearing as a result of aging) before middle age, while others may have normal hearing well into old age. The symptoms of these hearing losses will be, in some cases, indistinguishable from the symptoms of hearing loss caused by noise. Therefore, no matter how quiet the environment, a certain percentage of the employees will appear to have a noise-induced impairment. As indicated above, these impairments may actually result from diseases of the central nervous system, certain other illnesses, hereditary causes, head injuries, explosions, nonoccupational noise exposures, and, above all, presbycusis.

Although these factors influence only a very small percentage of the group, their presence makes an accurate definition of the "maximum nonhazardous noise exposure" almost impossible. That is, when the number of people in the group who incur hearing disability following repeated noise exposure is about the same as the number who may be expected to incur similar disability during the same period of time as the result of some other cause, it becomes statistically impractical to measure reliably the effect of noise. In such a situation, the uncertainty in the determination of whether or not noise has actually produced damage to hearing requires that an unreasonably quiet condition would have to be established to preclude the possibility of hearing impairment to the most susceptible member of the group. The cost of noise control to this end would, in most cases, be enormous. In addition, because of the statistical difficulties discussed above, less noise control may actually be sufficient in many cases. It seems impractical, therefore, to attempt complete elimination of all industrial noise exposures. A more reasonable approach is the reduction of any noise that impairs the hearing of a statistically significant percentage of the people exposed.

T. ENGINEERING CRITERIA FOR NOISE CONTROL

The difficulties enumerated above should explain the rather wide variations that one finds among the various criteria proposed for the prevention of damage to hearing.[22] Each criterion depends quite strongly on the assumptions that are made relative to individual susceptibility, significant hearing loss, and the duration of the exposure.

Engineering criteria for noise control, sometimes called damage-risk (DR) criteria, are extremely useful in spite of the lack of a firm scientific foundation. An example follows of one such set of criteria applied to a noise exposure that is continuous throughout an eight-hour day for five days a week. The noise is wide-band and free from any distinct impulses. The aim is to protect the employees by preventing noticeable hearing loss for everyday speech, while tolerating small changes in hearing acuity. Because of the difficulties enumerated in the previous section, no attempt will be made to protect all of them by noise control. Instead, audiometric examinations given to each employee periodically will aid in identifying unusually susceptible individuals. Those so identified can be transferred to a quieter job. If the number who incur noticeable hearing loss exceeds a significant fraction of the entire group, this procedure becomes impractical. Therefore, the criteria for noise control should be set so that no more than a significant fraction of the group are likely to incur noticeable hearing loss even after exposure for a score of years.

Under these circumstances, and with the given noise exposure, sound pressure levels should be below 95 db in the octave bands important to the conservation of hearing for speech.[20] These octave bands are the 300 to 600, 600 to 1200, and 1200 to 2400 c.p.s. bands with the greatest importance attached to the 300 to 600 band. Clearly, sufficiently intense levels outside of this frequency range will cause hearing loss for speech, but for typical noise spectra we may consider the extremely high and low frequencies of secondary importance.

If it were necessary to reduce the chances of causing noticeable hearing loss for everyday speech to a negligible value for even the most sensitive individuals, the octave band levels in the mid-frequency range (300 to 2400 c.p.s.) should probably not exceed 85 db for the noise exposure described. More careful study of the relationships between noise exposure and hearing loss may show that this criterion is unnecessarily low. At the present time, however, there is at least a 10 db spread between the levels that are estimated likely to affect a significant percentage of those exposed and levels that can be considered safe for almost everyone. Were the levels in the mid-frequency octaves as high as 105 db, it is likely that most of the group would incur at least noticeable hearing losses under the circumstances of the exposure described.

It is possible to summarize this set of criteria in terms of the approximate effect on a group of workers subjected to each of four ranges of noise exposure.

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[22] J. H. Sterner, Standards of noise tolerance, *Ind. Med. and Surg.*, **21**, 165 (1952).

If the levels in the mid-frequency octaves are less than 85 db, a negligible fraction of the group will probably incur noticeable hearing loss after exposure for a score of years under the circumstances described above. If these levels are between 85 and 95 db, the fraction will be small; if they are between 95 and 105 db, the fraction will be large. It may be remembered that changes in the temporal pattern of the noise, the length of exposure, and the definition of noticeable hearing loss and unusual changes in the frequency distribution of the noise will alter the effect of the noise on the group.

U. THE RELATION OF NOISE EXPOSURE TO SOUND ENERGY

A convenient assumption used extensively in recent years states that noise exposure is directly proportional to sound energy, the product of sound intensity and time. This assumption is not directly supported by, nor does it contradict, any existing data. Although it provides a method for comparing noise exposures of differing durations, large variations in the pattern of the noise exposure in time cannot be taken into account with confidence. If there is error in the assumption, however, the evidence does seem to indicate that slightly more sound energy can be tolerated when the noise exposure is irregular than when it is steady.

The assumption that noise exposure is proportional to sound energy can be used, for example, to revise the above DR criteria to apply to a three-hour daily exposure to noise. The exposure time will then be $^3/_8$ of the original eight-hour exposure. To maintain the same sound energy the intensity must be multiplied by $^8/_3$. The ratio of the resultant intensity to the original intensity is equivalent to an intensity level difference of about 4 decibels. Therefore, each of the criteria described above could be raised by 4 decibels without altering the total sound energy involved in the exposure. Using the assumption that sound energy is proportional to noise exposure, these new higher criteria can be applied to the three-hour exposure without altering the effects estimated for the original criteria and the eight-hour exposure.

IV. Noise Control

The basic methods of noise control are well known. A survey of the literature discloses the familiar theme "Control the noise at its source!" in the articles of a generation of authors. From an acoustical point of view this is still good advice, but practical difficulties may make it advisable to reduce the amount of noise transmitted to exposed persons instead. If this method of noise control is also impractical, protection of the individual is the only remaining alternative. Thus, listed in the order of desirability, the point of attack for the three methods of noise control is: at the source, along the transmission path, and at the man.

The difficulties associated with noise control should be recognized explicitly so that they may be circumvented whenever possible. One such difficulty is the serious lack of understanding of the principles of noise control among those responsible for plant design, plant equipment, and plant maintenance Inadequate knowledge of these principles may lead to misguided attempts at noise control and, consequently, a lack of enthusiasm for further efforts. Only education and a general diffusion of knowledge of noise control will remove this difficulty. The first step in this educational process is probably an appreciation of the complexity of the subject. It cannot be mastered by learning a few simple rules. One must familiarize himself with new units, new materials, and new concepts.

The difficulties raised by any lack of understanding of the principles of noise control are rather insignificant compared to those raised by the simple question "Does noise control pay?" Noise control seems to have more sources of expense than income. Acoustical materials are rarely inexpensive, and there may be hidden expenses caused by a slowdown or interruption of production. The income from noise control is almost always an intangible, and conservation of the hearing of employees must be viewed as a long-term investment that will pay excellent interest in future years. Management must face these facts squarely before launching a program for the conservation of hearing. Otherwise, the program has little chance of success.

The first step in such a program is an evaluation of the noise exposure. Methods for making the measurements involved are discussed in Volume III. The engineering criteria set forth in Section III.T of this chapter allow a classification of certain kinds of noise exposures and provide a goal for noise control.

Classification of noise exposures according to their severity makes it possible to assign priority to the most serious problems and defer those that are of minor importance. The goal for noise control provided by one of the engineering criteria makes it possible to avoid costly, unnecessary quieting. In addition, the amount of noise reduction required to meet the criterion will influence the choice of the approach to the problem. For example, if only 5 db of noise reduction is necessary, sufficient quieting will probably be achieved after a few minor changes. However, if a reduction of 25 db is desired, a rather complete revision of the entire operation may be necessary.

If the complete solution of one of the more difficult noise problems is presently impractical, the engineering criteria can be used to evaluate the probable effect of smaller noise reductions. Any significant reduction in the noise exposure is, of course, worth while since it decreases the number of people who may incur hearing impairment.

A. CONTROL OF NOISE AT THE SOURCE

1. *Desirability*

Compared to control of noise at its source, control along the transmission path or at the man is relatively simple to plan, but often difficult to carry out in practice. On the other hand, control at the source yields highly satisfactory results when it is well planned. The approach to the problem of noise control at the source should be made in a determined manner. Two important prerequisites are a strong will to do the job and an open mind.[23]

2. Is There a Quieter Way to Do the Job?

Control at the source may sometimes be accomplished by substitution of a quieter method of doing the job. Such substitutions have been listed by two authors,[23,24] and some notable examples follow: (*a*) welding instead of riveting, (*b*) compression riveting instead of pneumatic riveting, (*c*) mechanical forging instead of drop forging, (*d*) grinding instead of chipping, (*e*) electric tools instead of unquieted pneumatic tools, (*f*) conveyors instead of chutes, (*g*) mechanical stripping of work from punch press dies instead of air-blast stripping, (*h*) hot instead of cold working of metal, (*i*) belt drives instead of gears.

Other considerations may outweigh the importance of noise in selecting a tool or a method of doing a job. However, whenever this is not the case, those responsible for plant layout and equipment planning should be alert for quiet alternatives to noisy jobs.

An examination of the quieter methods suggested above discloses two general rules. A substitute method that eliminates the impact of metal on metal or reduces the rapid flow of air will often bring about considerable quieting. These two principles may bring to mind other substitutions that provide the solution to particular noise problems.

3. Examples of the Control of Noise at the Source

The control of noise at the source is usually difficult to plan because of the lack of general rules. For instance, identical machines may require different methods of noise control because of different production problems or different economic considerations. Although it is not possible to present a cookbook of noise control recipes, certain typical case histories can be reported. Those who have similar problems may be able to determine whether similar steps are applicable to their situations.

a. Circular Saws. A circular saw that is noisy during the sawing operation but quiet otherwise is operating as well as can be expected except that some quieting may be achieved occasionally by substitution of another kind of saw. A saw that is noisy whether it is sawing or not often can be quieted. Play in the arbor should be corrected by new bearings. If the saw does not run perfectly true, it may be necessary to remachine the saw collar. A kerf significantly wider than the rim of the saw blade indicates a rim that is vibrating excessively.

Stiffening collars may be used in some situations to reduce rim vibration.

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[23] C. R. Williams, Noise can be controlled, *Am. Ind. Hyg. Assoc. Quart.*, **15,** 32 (1954).

[24] F. G. Tyzzer, Reducing industrial noise: general principles, *Am. Ind. Hyg. Assoc. Quart.*, **14,** 264 (1953).

It is necessary that the collar cover a significant fraction of the area of the saw. A simple test to see how large a collar is necessary can be made by clamping each of several sizes of saw blades next to the noisy saw. If the smallest one that quiets the saw allows a large enough cutting depth, regular stiffening collars should be obtained. They may be purchased from the saw manufacturer or machined from aluminum or steel (Figure 26).

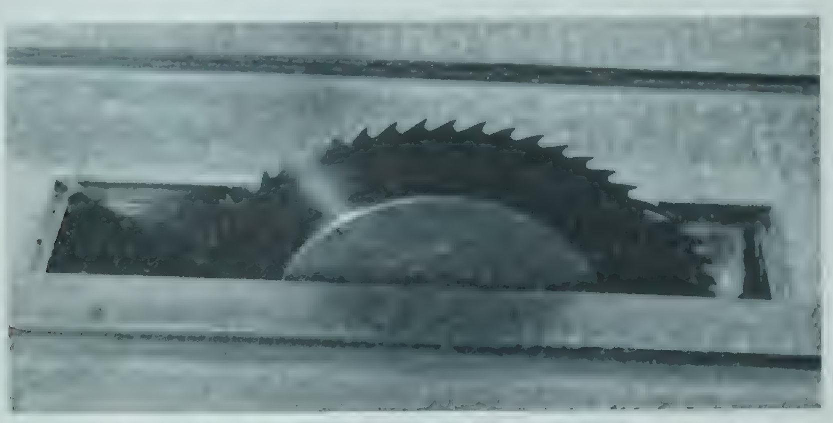

Figure 26. A stiffening collar for a circular saw blade. The material is sheet aluminum about $^1/_8$ inch thick.

In general, combination, hollow-ground, and swage-set saws are quieter than ordinary ripsaws. A crosscut saw with a small number of properly aligned teeth will usually be quieter than a similar saw with many teeth. Saws with a small number of teeth and deep gullets produce little noise as a result of rim vibration, but occasionally generate a sirenlike noise. Stiffening collars have no effect on this source of noise.

b. Machining Resonant Parts. Occasionally the machining of hollow parts that are highly resonant causes a screaming sound. Such a piece of material will, when struck, ring like a bell with the same pitch as the continuous sound produced during the machining operation. This kind of noise can occur as a result of operations on lathes, milling machines, planers, grinders, and scrapers.

Using a wooden mallet, strike the resonant part at the normal point of contact with the tool and then grip the part firmly. A part that can be quieted with one's hands in this test is likely to be one that can be quieted during the machining operation by means of a rubber boot. The boot should be shaped to fit tightly against a large portion of the surface of the part, but should not interfere with the machining operation. Under these circumstances a large fraction of the vibrational energy in the resonant part will be absorbed by the highly damped rubber boot. That portion of the part to be machined that quiets the ringing most easily when it is gripped with the hand will provide the most effective damping.

An example of this kind of noise problem is the "finish-turn" operation in the manufacture of artillery shells. Since the shell is hollow and highly resonant, it is easily excited by the turning tool as the shell rotates in the lathe. A piercing scream is produced that reaches levels as high as 120 db at the operator's ear. When a length of heavy rubber hose whose outside diameter is about the same as the mouth of the shell is placed inside the shell, the screaming sound is practically eliminated.

It may be necessary to have a series of boots to be used during different phases of some more complicated machining operations. Sometimes the vibration of the part being machined involves such tremendous forces that only a small fraction of the vibrational energy will be absorbed by the rubber. Stiffer rubber or a sandwich made out of a thin layer of felt and an outer layer of metal may be necessary.

c. Stock Tubes for Screw Machines. Screw machines that turn long pieces of "hex"stock are frequently noisy. Most of the noise is a result of the corners of the stock striking the guide or tube that feeds the screw machine. Machines using round stock also may be noisy if the stock does not run true in the stock tube. This difficulty occurs frequently when the stock is stored or transported without being well supported along the entire length. Carrying long pieces of stock on a small dolly will bend them into a gentle arc that results in noisy operation of the stock tubes.

Substituting stands that clamp the stock rigidly inside a freely rotating bearing in place of the noisy stock tube is one solution to the problem. Another is a stock tube with a spiral inner surface made of spring steel, a layer of a resilient material that absorbs the impacts of the stock striking the inner surface, and a solid outer tube. Such a stock tube is commercially available.[25]

d. Chutes, Hoppers, and Tote Boxes. Metal parts falling into chutes, hoppers, and tote boxes cause considerable noise in plants that produce large quantities of small parts. Of course, the noise can be reduced by decreasing the distance the parts fall. When this approach is impractical, lining the metal surfaces with a compliant material, such as rubber, may be effective. Abrasion-resistant and high-temperature rubbers are available for installations in which these considerations are important.

Even such specialized materials may not be practical in some cases. For instance, the use of rubber may be impractical in chutes because a rather low coefficient of sliding friction is necessary. Parts that have sharp corners or are extremely hot also may require another kind of treatment. One that is useful in both of the situations described above is a "sandwich" treatment. The original metal surface is covered with a thin layer of cardboard, asbestos paper, or felt, about $^1/_{16}$ of an inch thick. The cardboard is then covered with a layer of sheet metal. In most installations 20-gauge galvanized steel will be satisfactory.

The large local forces that occur when a part strikes the top layer of metal are dissipated in the compliant layer that forms the middle of the sandwich.

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[25] B. J. Schweitzer, A silent stock tube for automatic screw machines, *Noise Control,* **2,** 14 (March, 1956).

The stiff bottom layer prevents bending of the compliant layer and forces it to be compressed between the top and bottom layers. Effective damping of the movement of a piece of heavy sheet metal is accomplished by this technique, whereas even thick layers of undercoat applied to a single piece of sheet metal of equal weight produce an almost negligible improvement.

Plant installations of the "sandwich" kind of treatment produce noise reductions of about 10 db providing other noise sources are less important. Figure 27 shows one such installation.

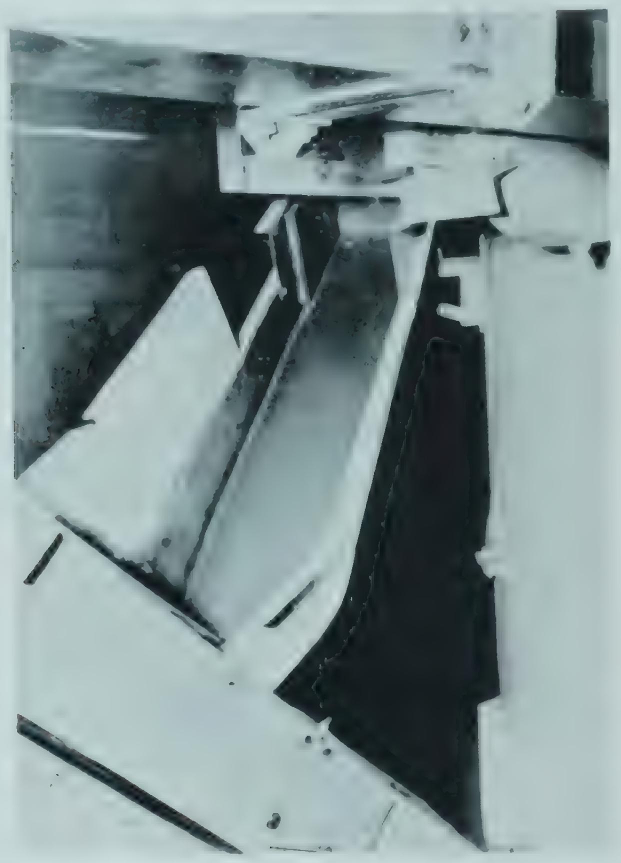

Figure 27. Shells (30 caliber) drop several inches onto the chute and then slide down the incline to be picked up by the upward slanting conveyor. Rubber has been placed at important points along the sides of the chute. The bottom of the chute is lined with a metal-cardboard-metal "sandwich." (Courtesy Remington Arms Co., Inc.)

e. Sand Chutes. The movement of sand through ducts and chutes may be a source of noise in foundries. The installation of heavy gauge ducts is usually impractical, but the application of a thin layer of abrasion-resistant rubber to critical points on the inside of the duct is simple and effective. The rubber-lined duct usually outlasts a metal duct since the particles of sand bounce instead of cutting into the rubber.

f. Punch Presses. The principal sources of noise in the common punch press are: (*1*) the impact of the die striking the work, (*2*) the impact of the parts of the crank and ram against one another as the slack is taken up at the moment the die meets the work, and (3) the noise of the air blast used to eject the completed part.

The noise of the die striking the work may sometimes be reduced by specially prepared dies. These dies should be ground to cut by a gradual shearing of the metal rather than by punching through the work at all points at the same time.[26] A good "shear-ground" die is difficult to make, but will last longer than a "flat-ground" die. A "multiple-stage" die should be stepped so that the stages shear through the work one after another instead of all at once.

Unnecessary noise is produced if the work is positioned well above the bottom of a stroke. The minimum amount of noise is generated if the die begins to shear through the work very near the bottom of a stroke and completes the punching of the part just as the crank passes dead center. The velocity of the impact is minimized and, therefore, a machine of larger capacity may be required.

Quieting of an operation on a small, high-speed punch press may sometimes be achieved by transferring the job to a press with a greater capacity, but with a slower speed. Equal production can be regained by punching more than one part with each stroke of the larger press.

Liberal lubrication of many punch-press operations, particularly drawing, will produce work of better quality more quietly. An overhaul is needed if the noise produced by a punch press emanates from the vicinity of the crank, bearings, or gears rather than from the dies. In such cases the noise at the instant of impact results from the elimination of the slack in the mechanical chain connecting the motor to the die. A maintenance program that includes regular inspection and overhaul is, therefore, an important part of a hearing-conservation program in plants using punch presses.

The noisy air blast used to eject parts from a punch press can be eliminated by substitution of mechanical ejection. This substitution will not always be possible and other alternatives are discussed below (page 684).

g. Materials Handling. An important source of noise in steel-fabricating shops is the handling and straightening of metal plates and beams. Improved materials-handling procedures may pay dividends of reduced noise and less damage to materials. In production operations the handling equipment can be custom-made to eliminate the dropping of materials.

The alignment of bent and damaged plates is often accomplished with a sledge hammer and careful handling may also help to eliminate this source of noise. Noise from metal-to-metal contact can be minimized by the use of wooden frames, pallets, or shims. The principal requirements of such a noise-control program are foresight and a willingness to try new techniques.

h. Can Conveyors. The conveyor lines that carry cans are usually constructed of two stationary guide rails and a moving wire rope that travels underneath the cans. The irregularities in the wire rope running under the cans produce considerable noise. Replacing the wire rope with a flat belt will result in a quieter operation, but an adjustable idler wheel must be installed because the belting is more likely to stretch than the wire rope. In addition, splicing and loading problems limit the system to fairly short runs. In spite of these difficulties the flat-belt line may be a worth-while substitution where the can conveyor is the prime source of noise.

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[26] C. E. Crede, "Control of Impact Noise," *The Acoustical Spectrum*. Univ. of Mich. Press, Ann Arbor, 1952, p. 117.

i. Conveyors for Small Parts. Small parts that are handled in bulk in metal chutes, conveyors, and elevators are often noisy as a result of the impact of the parts against each other. A single part traveling alone will move quietly if the conveyor or chute has been treated to minimize noise (page 679). Thus, the conveyor system should avoid the accumulation of parts at any point. If the storage of parts is necessary, a rubber-lined reservoir that is completely enclosed should be used.

In general, worm-feeding mechanisms are quieter than gate-feeding because parts can be taken continuously from a reservoir rather than in a noisy, rhythmic fashion.

j. Chipping Hammers. Noise from the impact of the chisel of a chipping hammer striking a metal casting or a steel tank can be extremely intense. Although it is unlikely that satisfactory engineering control for this problem will be found in the near future, steps can be taken that will be of some help in conserving hearing.

Chipping operations should never be carried out on metal surfaces. Wooden benches or wooden-block or dirt floors are better.

A jig that will clamp the work and minimize vibration may be practical for operations where production is high. It is necessary that large areas of the vibrating surface be damped and the forces involved are quite large. Damping materials, such as rubber, are usually ineffective, but lead sandwiched between the clamping jig and the work may be satisfactory. Submerging the work to be cleaned by chipping in a liquid bath is another method of noise control that may have some merit. The work must be supported by a frame that is isolated from the tank to prevent the transmission of vibration to the outside.

k. Rotary Cutters. Cutting strands or sheets of plastic into small pellets is usually accomplished by feeding the material to a set of rotating knives. The entire cutting assembly should be isolated from the rest of the device to minimize the transmission of vibration to the housing where it may be radiated as sound.

The knives and the plate that they cut against should be rigid and heavy. The knives should not strike the work all at once, but rather begin to cut at one side and progress smoothly toward the other in a shearing fashion. When one knife has completely passed through the material, the next knife should be in position to start at the opposite side. Reducing the rotational speed of the cutter reduces the noise somewhat because the knife strikes the work with a lower velocity. Increasing the number of knives on the cutter will restore the original productive capacity of the machine.[27]

l. Noise from Piping. The hammering of liquid in pipes can produce an unnecessary noise at great distances from the pumping equipment. For quiet operation flexible sections of piping and air cushions should be installed in the vicinity of the offending valves and pumps. Commercial products and materials are available to aid in the solution of these problems.[28]

m. Pneumatic Hammers Used in the Manufacture of Paper Boxes. In the paper-box industry the scrap is separated from the box by means of a vibrating chisel actuated by a chipping hammer. The reciprocating piston in the hammer strikes the end of the chisel and produces a ringing at high frequencies. The pulsating stream of air escaping from the exhaust port of the hammer produces a low frequency sound. In contrast to chipping castings and steel tanks, the noise is produced by the tool itself. Noise reduction is obtained by using a collector ring, covering the exhaust port, to channel the exhaust air to a single opening and then to a long hose (Figure 28). The muffling action of the long hose and the remote location of the noisy, open end of the hose result in an operation that is significantly quieter.[29]

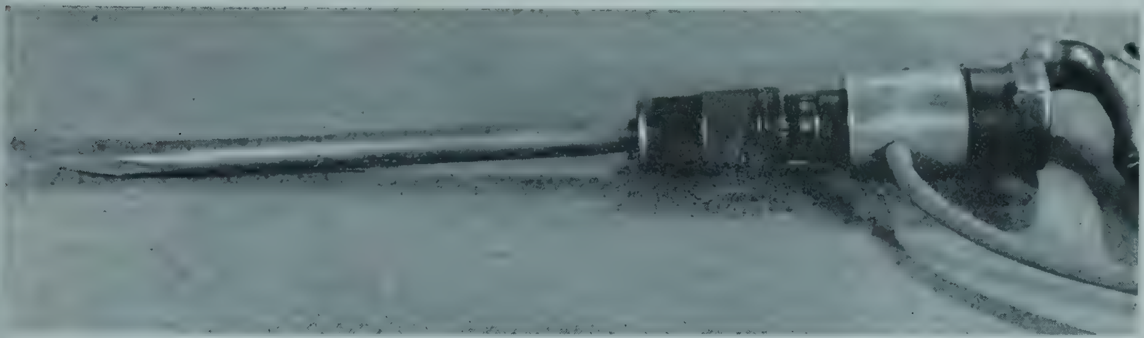

Figure 28. Exhaust collector in place on a pneumatic hammer. The use of the exhaust hose reduces the noise from this tool during certain operations in the manufacture of paper boxes.

n. Air-Operated Tools. The sirenlike noise produced by some air-operated tools can be quieted by attaching a small silencer to the exhaust.[30] Since back-pressure is an important consideration, silencers of the "straight-through" variety are best suited to the task. They can be constructed from two concentric pieces of tubing with fiber glass packed between the walls. The inside tubing should be

[27] J. R. Cox, Noise control for a strand cutter, *Am. Ind. Hyg. Assoc. Quart.*, **15**, 42 (1954).

[28] D. B. Callaway, F. G. Tyzzer, and H. C. Hardy, Techniques for evaluation of noise-reducing piping components, *J. Acoust. Soc. Am.*, **24**, 725 (1952).

[29] R. Plunkett, Noise reduction of pneumatic hammers, *Noise Control,* **1**, 78 (January, 1955).

[30] W. C. Chaffee, Reduction of noise in industrial pneumatic tools, *Noise Control,* **1**, 16 (March, 1955).

perforated with many holes and have a diameter large enough so that the back-pressure of the silencer is small. The length of the silencer should be at least 10 times the diameter of the inside tubing. The muffler can be strapped to the air hose supplying the tool.

o. Small Air Nozzles. The ejection of parts from a punch press is often accomplished by a blast of air. In other machining operations, an air blast may be used to blow away chips. Since both of these applications utilize the thrust of a moving stream of air, a silencer will not be a practical method for reducing the noise.

The design for an air nozzle shown in Figure 29 is about 10 db quieter than a straight piece of $^{1}/_{4}$-inch copper tubing even though both deliver the same thrust. With the thrust delivered per unit area of opening held constant, less noise is produced when small holes are used. On the other hand, interaction between the streams from several holes causes the total thrust to be less than the sum of the thrusts from the individual holes. For the nozzle shown, holes with a diameter of $^{1}/_{16}$ inch seem to be optimum.

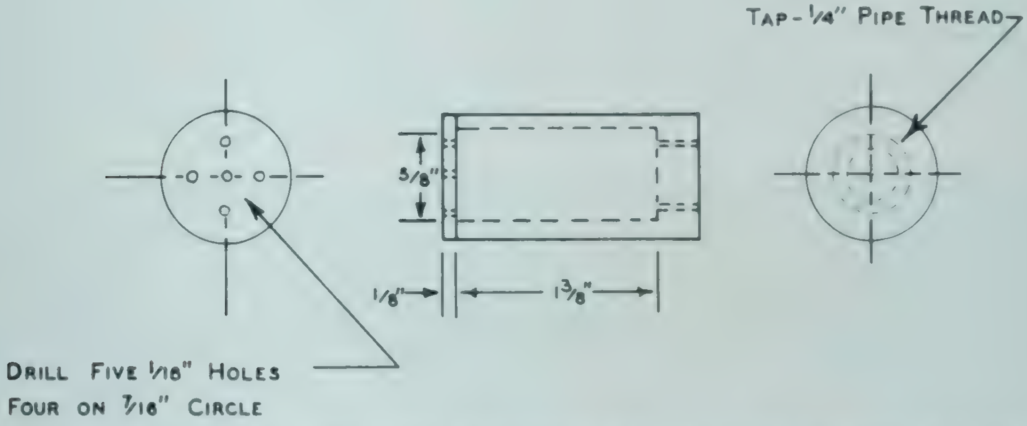

Figure 29. Design for air nozzle used to quiet air jets. The noise produced is about 10 db less than a straight piece of $^{1}/_{4}$-inch copper tubing that develops equivalent thrust. Almost any material may be used and only those dimensions shown are critical.

Quieting the nozzle of an air jet may be only part of the job. Sometimes considerable noise is produced when the air stream strikes an irregular object. Sharp corners, holes, and grooves should not be in the path of the air jet.

p. Air-Cylinder Exhausts. Quieting the exhaust of an air cylinder is a simple matter. Since the thrust developed by the escaping air is unused, a silencer may be attached without affecting the operation. Usually back pressure is unimportant and any commercially available silencer may be used. When back pressure is a consideration, commercial mufflers of the "straight-through" variety may be used. With such a simple solution to the problem available, there is little excuse for noisy exhausts on pneumatic equipment.

B. CONTROL OF NOISE BY ENCLOSURE

1. Fundamentals

The material presented in Section II makes it clear that a large reduction in noise can be achieved by complete enclosure of a noise source. However, Figure 19 shows that even small openings in the enclosure will cause large reductions in the effective transmission loss of the partition. Therefore, special attention should be paid to doors, windows, conduit and piping penetrations of the wall, and openings that are necessary for the feeding of material to and from the machine.

The examples discussed below are but a few of the industrial machines that can be quieted by enclosure.[31,32] The materials used in the construction of the enclosure depend upon the noise reduction that is desired. The approximate noise reduction of a particular wall construction can be found by use of the principles described in Section II.

The difficult part of the construction of such enclosures is the treatment of the openings that may allow noise to leak to the outside. Usually a duct with a small cross section and an inside surface lined with absorbing material is the treatment chosen for the openings necessary to the operation of the machine. Gaskets, caulking compound, and similar materials are applied to doors, windows, and cracks to eliminate all unnecessary openings.

Isolation of the machine from the floor may be necessary if appreciable vibration is transmitted to the rest of the building. Otherwise, vibration of the walls and floor may cause sound to be radiated into the room surrounding the quieted machine or to the room below the machine.[11,33]

The rules for enclosing a noisy machine can be summed up as follows: (*1*) Enclose as much of the machine as possible. (*2*) Provide adequate acoustical treatment for all doors and openings that are necessary to the operation of the enclosed machine. (*3*) Isolate the machine from the floor to minimize the transmission of vibration, if necessary.

2. Examples of the Control of Noise by Enclosure

a. Enclosure for a Wood Planer. A large wood planer used to surface rough lumber was operated steadily throughout each working day. Because of the severity of the operator's exposure to noise, an enclosure was constructed (Figure 30). The walls of this enclosure were made of heavy plywood covered on the inside with glass wool. The exposed surface of the glass wool was protected by a perforated facing. Openings in the enclosure were necessary at the

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[31] J. R. Engstrom, Noise reduction by covers, *Noise Control,* **1,** 19 (March, 1955).

[32] R. J. Wells, Enclosures for noise reduction in the factory, *Am. Ind. Hyg. Assoc. Quart.,* **15,** 59 (1954).

[33] R. N. Hamme, *A Study of the Problem of Resilient Mounting Against a Non-rigid Foundation Structure.* Engineering Research Inst., Univ. of Mich., Ann Arbor, 1950.

feed and discharge of the planer. These openings were made just large enough for the wood to move in and out of the planer. A short ductlike arrangement was attached at these openings to minimize the transmission of sound through them. The top and sides of the duct were covered with a layer of glass wool. A large glass window was installed in the wall just above the feed opening so that the operators could see the wood as it entered the feed rolls. Doors for maintenance work were carefully hung and gasketed to prevent sound leakage. Air for ventilation and for the removal of wood chips passes into the enclosure through a labyrinth lined with glass wool to insure that little noise escapes through this path. This air is exhausted through a heavy duct to the roof. The noise reduction obtained with an enclosure such as this depends upon the quality of workmanship, but should be at least 15 or 20 db in the mid-frequency range.

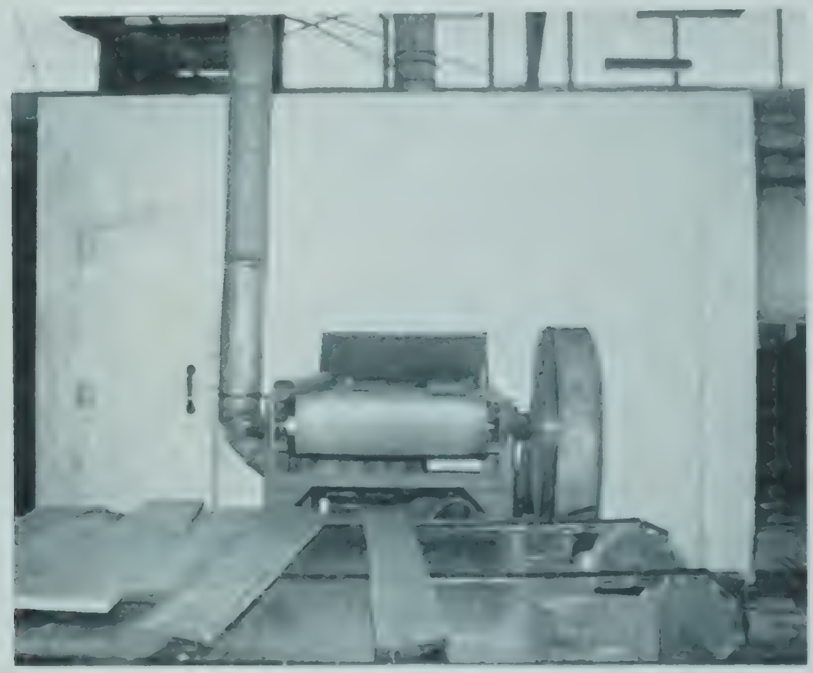

Figure 30. An enclosure around a large planer. This view shows opening at discharge end of machine. Note doors for access to interior of enclosure and moving belt that conveys wood through output duct. (Courtesy Kroehler Manufacturing Co.)

b. Enclosure for the Testing of Small Engines. Small gasoline engines for outboard motors, chain saws, and other portable applications are usually quite noisy. Effective quieting is not readily achieved because these engines must be compact and light in weight. Therefore, the testing of these engines by the manufacturer is likely to be a severe noise exposure for the testing crews.

In one instance, chain-saw testing, small individual test cells provide a simple solution (Figure 31). The exhaust of the engine is passed through piping that leads to a large stationary silencer. Usually, because of the shape of the exhaust stack on the engine, it is not possible to make a tight connection between the silencing system and the engine in a reasonable amount of time. In addition, considerable noise is radiated by the air intake and the cylinder casting. Therefore, enclosure of the saw is the most practical solution.

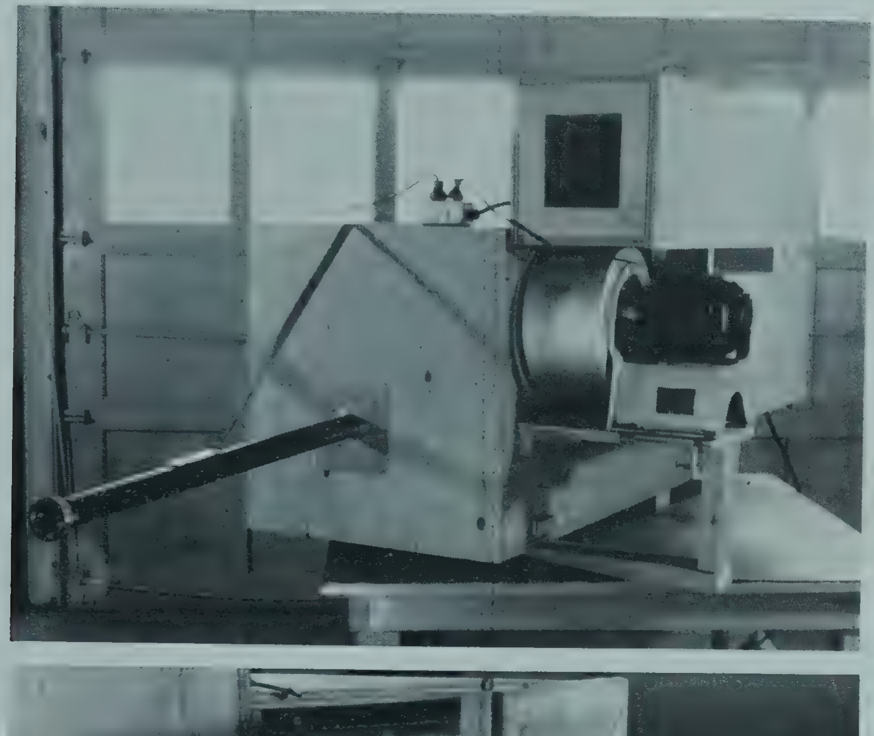

Figure 31. Two views of an enclosure for a chain saw. The duct in the top picture reduces the noise that would otherwise travel along the path taken by the cooling air as it leaves the enclosure. The bottom picture shows the door at the front of the enclosure. Note the window for viewing and the short duct for adjustment on the engine.

The enclosure has a door for removal of the engine and a short duct through which the operator can make adjustments. The duct is lined with glass wool, which is covered by a perforated facing. A glass window in the door plus a light in the enclosure facilitate viewing the engine. A duct lined with glass wool at the output of the ventilation system reduces the transmission of noise along the path followed by the air used to cool the engine. A bellows in the exhaust line simplifies alignment of the engine and prevents the transmission of vibration into the silencing system. Noise reductions at the operator's position of more than 20 db can be obtained in the mid-frequency region.

c. Enclosure for a Wood Hog. A woodhog is a device for shredding scrap lumber. The impact of a set of rotating knives on the scrap wood makes an extremely intense noise. It is usually a simple matter to enclose the hog. To prevent the leakage of noise through small openings, doors, windows, and junctions between the walls, ceiling, and floor must be sealed carefully. Scraps of wood are fed to the hog on a moving belt. The belt passes through the wall of the enclosure surrounding the hog. A duct lined on the inside with glass wool surrounds the moving belt for a distance of about 10 feet. The glass wool is covered by heavy, perforated metal to protect it from damage.

The combination of the enclosure and the duct surrounding the conveyor should provide at least a 15 db reduction in the noise providing the doors in the enclosure remain closed. Since feeding wood to the hog too fast will cause a "haystack" of scraps at its entrance, the conveying system must be carefully designed so that it will be unnecessary for a man to open a door in the enclosure to clear the hog during its operation.

d. Enclosure for Tumbling Barrels. Barrels for the tumbling of castings and forgings produce a considerable amount of noise as a result of the impact of the parts against the side of the barrel. Individual enclosures built around the barrels can provide adequate quieting. However, a method for easy access to the barrel door must be incorporated. The door of the enclosure should be just over and conform to the barrel door. It should open so easily that no delay in loading or unloading the barrel is encountered. The door also must be sealed very tightly and, therefore, an automatic means for opening and sealing the door is desirable.

Tumbling barrels processing a continuous stream of parts can be quieted by employing a scheme similar to that described for the wood hog. Conveyors can be used to feed the parts to the barrel and to take them away. A duct lined on the inside with glass wool surrounds the conveyors and reduces the noise that would otherwise pass through these openings. The remainder of the tumbling barrel can be enclosed without difficulty.

C. CONTROL OF NOISE BY SOUND-ABSORBING MATERIALS

The installation of acoustical absorbing materials on ceilings and walls may bring about significant quieting under certain conditions. These materials are most likely to be effective when the offending noise source is distant from the listener. Figure 14 shows clearly that the effect of increasing the average absorption coefficient of a room is large near the walls, but negligible near the source. Unfortunately, most industrial exposures to noise involve persons stationed quite close to noisy machines. A man stationed farther away has a smaller chance of incurring hearing impairment and, therefore, noise control is less important for his safety.

In certain unusual cases there may be no one without ear protection who is regularly stationed close to the noisy machine and the noise exposure of those located farther away may be severe enough to warrant noise control. If for some reason it is not practical to enclose the noise source, up to 10 db of noise reduction can be derived from the application of absorbing materials to the walls and ceiling of a typical shop space. These materials are also particularly effective in reverberant rooms with low ceilings.[34] In any case the methods of Section II.F give an estimate of the noise reduction that may be expected as a result of the installation of acoustical materials.

D. CONTROL OF NOISE BY EAR PROTECTION

1. When to Use

The problems and disadvantages associated with ear protectors that are discussed below make it clear that reduction of the noise at the source is by far the most satisfactory solution to most noise problems. There are situations, however, in which the use of ear protectors is the only practical solution either because treatment of the source is impossible or because it cannot be accomplished immediately.

2. Characteristics of Ear Protectors

Ear protectors may be divided into classes according to their physical structure. The information pertaining to a class of protectors is quite similar and relatively independent of the manufacturer.

The noise reduction of ear plugs shown in Figure 32 was obtained with the plugs carefully inserted by trained personnel under laboratory conditions. Therefore, these curves represent the *maximum* amount of protection that can be expected with the best possible co-operation from employees. Under conditions of actual use the average noise reduction probably will be 5 to 10 db less than that shown. These curves are averages of available data for the major classes of plugs.[35,36]

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[34] H. J. Sabine, The use of acoustical materials in the control of industrial noise, *Proc. Third Annual Natl. Noise Abatement Symposium,* 1952 (Armour Research Foundation, Chicago, Ill.).

[35] *The Acoustic Performance of Various Ear Plugs.* Psycho-Acoustic Laboratory, Harvard Univ., Cambridge, Mass., 1943.

[36] D. E. Wheeler and A. Glorig, The industrial hygienist and ear protection, *Am. Ind. Hyg. Assoc. Quart.,* **16,** 40 (March, 1955).

a. Cotton. The upper dashed curve in Figure 32 shows the noise reduction typical of ordinary, dry cotton wads placed in the ears. The protection is poor throughout the low frequency range, but improves slightly at high frequencies. This possibly accounts for the misleading claims of some enthusiastic users of ordinary cotton. The reduction in high frequency noise decreases the annoyance of the noise, and the user believes that his increased comfort means satisfactory protection.

b. Impregnated Cotton. The solid curve in Figure 32 shows the typical noise reduction for properly fitted wax-impregnated cotton plugs. These plugs are cylinders $^1/_2$ inch in diameter and about $^3/_4$ inch long. Their average weight is a little over 2 grams. They must be warmed and rolled in the hand before insertion; when the material has the consistency of putty, the plug may be pressed into the ear. Care must be taken to insure that the plug conforms to the ear canal. At tropical temperatures, the wax softens and becomes sticky and the plugs are, therefore, unsatisfactory. Under all conditions of use, they collect and retain any dirt to which they are exposed. These plugs are relatively expendable, however, since a new pair each day for each worker would not be unreasonably expensive. If the plugs must be removed many times each day, it may not be economical to use new plugs each time. Also, it is inconvenient to remold the plugs each time.

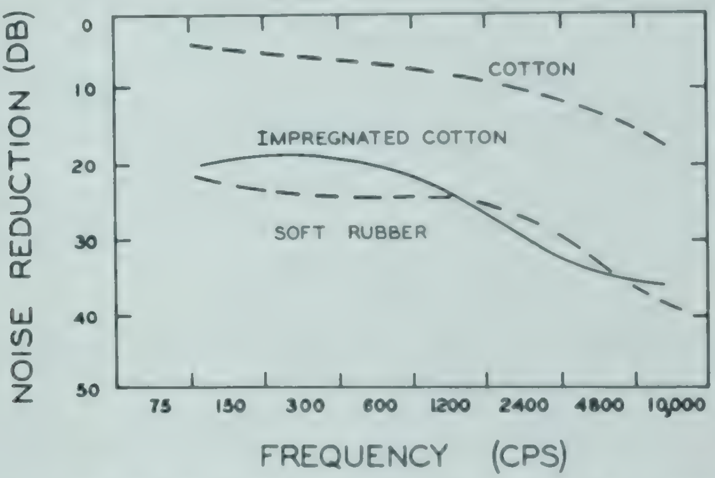

Figure 32. Maximum noise reduction to be expected from ear plugs. For average noise reduction subtract 5 to 10 db. Data were averaged from several sources.[35,36]

c. Soft Rubber. The lower dashed curve in Figure 32 shows the typical noise reduction for properly fitted soft-rubber plugs. These plugs are capsules of a soft rubberlike material weighing about $^1/_2$ gram, shaped to facilitate insertion and retention in the ear canal. Most manufacturers make the plugs in three sizes for comfortable fit in small, medium, and large ears. They should be made of a special nontoxic elastomeric material that is resistant to the action of ear wax. The plugs must be carefully inserted to provide adequate protection. They have small tabs on the outside end of the plug to facilitate removal. Unless these plugs are cleaned regularly with soap and water, they will collect wax and dirt. Their average cost is slightly less than a dollar a pair. Therefore, they are not as expendable as the impregnated-cotton plugs.

Attempts have been made to design a plug that excludes noise, but not speech. One such attempt is a "filter" plug, which has a small perforation that allows low frequency and mid-frequency sounds to be transmitted. The noise reduction characteristic is no better than that for cotton up to the 600 to 1200 c.p.s. band. Above this band the characteristic is about the same as the average for soft rubber plugs. Another attempt at an ear plug that will pass speech utilizes a tiny valve that closes during an intense pressure pulse of long duration. At all other times the valve is open and the plug has a noise reduction similar to the "filter" type.

d. Muffs and Helmets. Muffs that cover the outer ear and are held in place by means of a headband have a noise reduction characteristic silghtly better than that of the filter type of ear plug, but usually not as good as the solid plug. It is difficult to obtain a good seal between the muff and the ear, and for this reason, the low frequency noise reduction may be poor. Muffs that have a very firm headband will provide protection equivalent to that of a solid plug, but they may be uncomfortable if worn for long periods. A new muff with a fluid-filled seal apparently overcomes this difficulty. Helmets are, in general, inferior to muffs.

This type of protector can be put on and removed quickly since nothing need be inserted in the ear canal. Therefore, the muffs and helmets are useful in situations that require frequent removal of ear protection or for personnel who cannot wear regular protection. They may be worn in addition to plugs if extra protection is needed. This combination approaches the theoretical limit of ear protection.[37]

3. Medical Considerations

A few employees will require treatment before they can wear ear plugs safely. Current medical opinion indicates that eczema and draining of the ears are the major reasons for not wearing ear plugs. Usually these difficulties can be corrected by treatment in the plant or by the employee's physician. The employee can then participate in the ear-plug program within a short time. During treatment, the employee may wear ear muffs.

A few who should be treated may not be aware of their condition. Complete screening of all exposed employees may be accomplished by means of an otoscopic examination performed by the plant physician. If an audiometer program is to be conducted, this examination will probably be planned for the time of the first audiogram.

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[37] H. E. von Gierke, Personal protection, *Am. Ind. Hyg. Assoc. Quart.*, **15**, 44 (1954).

4. Speech Communication

Most of the important speech sounds are contained in the mid-frequency region. The intelligibility of speech depends on the intensity levels of the speech and the background noise. If the background noise is increased, the speech level also must be increased to preserve intelligibility. There is, however, an optimum intensity range for speech. The ear can discriminate small differences in intensity at normal speech levels better than at very high or very low levels. For noise levels above 100 db in the mid-frequency region, the speech level may be top-of-the-lungs volume at mouth-to-ear range without achieving intelligibility. Under these conditions, the speech intensity may reach the listener's threshold of pain.

The use of ear protection will reduce both the noise level and the speech level received by the ear. The ear will, therefore, operate in a more normal range. A direct comparison of the intelligibility of speech in noise with and without soft rubber ear plugs was performed at Harvard.[35] The conclusions were as follows:

1. that wearing of the plugs afforded welcome relief from the discomfort of exposure to intense noise;
2. that the annoyance of breath blasted into the ear, and the pain of shouting directed into the ear, are eliminated by use of properly fitted plugs;
3. that, when a brand of soft rubber plugs is worn in noise, the intelligibility of speech is at least as good as, and perhaps better than, the best performance of an unplugged ear;
4. that the maximal mouth-to-ear distance for intelligible speech is in nowise decreased by use of these plugs.

The above conclusions do not necessarily apply to the "filter" or "valve" type of ear plugs. These plugs have little noise reduction in the low frequency range and increased reduction in the highest two or three frequency bands. If the noise is primarily in these two or three bands, some increase in intelligibility will be gained by the filtering action of the ear plugs. If this is not the case, little improvement should be expected. For predominantly low frequency noise, this type of plug may even decrease intelligibility by attenuating the two higher speech bands, but not the noise. In addition, the mid-frequency region is a more important contributor to hearing loss than the high-frequency region.

5. Establishment of an Effective Ear Protection Program

An ear plug is only as good as its fit. Unless the ear plug is properly inserted before every noise exposure, the program will not be successful. Therefore, it is necessary that the employees be educated concerning the hazard of noise and carefully instructed as to the method of inserting ear plugs.

It is wise to present the employee with many different kinds of ear protection and let him choose the type he likes best. Having had an opportunity to select his own ear protectors, the employee may feel a greater inclination to use them properly. In addition, there are wide variations in the shape and size of ear canals. No one plug can fit all ears.

It is especially difficult to "sell" employees on an ear-plug program when the noise is intermittent in nature. The desire or necessity to converse during quiet periods is inhibited if full protection for the noisy periods is maintained. It is tiring to use a raised voice if the only reason for its use is the set of plugs in the listener's ears. If the plugs are continually removed and reinserted, a proper fit probably will not be maintained. If under these circumstances the employees will not accept complete ear protection, the filter, helmet, or muff type of protection may be helpful.

There is no simple, positive way to police an ear-plug program. A periodic audiometric program will help to discover the unusually susceptible individuals and those who are careless about the wearing of ear protection. If a man shows a disproportionate threshold shift, his case should be investigated carefully. If improper ear protection or no protection has been worn, steps should be taken to see that good compliance with the program is obtained in the future. A combination of plugs and muffs may be used if the need for additional protection is indicated. In some cases these measures may prove inadequate and it will be necessary to remove the man from the noisy environment.

CHAPTER XIX

Radiant Energy

LEON F. CURTISS

I. Fundamental Concepts of the Production of Injury by Radiation

A. IONIZATION AS A CAUSE OF INJURY

Radiant energy produces undesirable effects in the human body whenever it is absorbed in excess of certain amounts to which the human organism has been accustomed in its natural surroundings. These undesirable effects may arise in different ways and may become evident in a variety of manifestations; but, regardless of the particular type of radiation producing them, the basic process in the human system by which injuries from radiation occur is much the same. This is more readily understood when the effect of various types of radiation on individual living cells is investigated. Such study reveals that the injury to cells is proportional to the ionization produced in the cell. Therefore, injuries result only when the radiation releases ions within the cell structure. It does not matter greatly how these ions are produced. Ionization produced indirectly by secondary electrons ejected by x-rays or gamma rays will have approximately the same general effect as that produced directly by radiation consisting of primary charged particles, such as beta rays and alpha rays. The effects on the human body as a whole, however, may vary considerably depending on the type of radiation, the way it is applied, and the kind of cells destroyed, or injured, by the effects of the ionization produced by the radiation.

B. TARGET THEORY

From investigations of the destructive effects of radiation on simple forms of life, particularly single-celled organisms, it has been found that all parts of the cell are not equally sensitive. There is a definite region, sometimes referred to as the target area, in which the production of sufficient ionization may release reactions fatal to the entire cell. Ionization in regions outside the target area produces little response. This description forms the fundamental concept in the target theory of the action of radiation, which has been quite successful in explaining the observations when bacteria are irradiated and the lethal effects measured. The application of this theory to higher forms of life is complicated by the secondary physiological reactions that are set up in tissues by the destruction of some of the component cells. Furthermore, it appears that under certain conditions multiple impacts on the target area are required in order to produce lethal effects. However, extensions of this method of approach to the problem meet with increasing success in explaining the effects of radiation in many-celled tissues.

C. INJURIES IN HIGHER FORMS OF LIFE

When we come to more complicated organisms and, in particular, to the human body, the lethal effect of ionization on individual cells plays the dominant role in the injuries produced. An additional factor enters, however, in that the various groups of cells in the organism co-operate to repair the damage so that the destroyed cells may be replaced. Consequently the human body may be exposed repeatedly to intensities of radiation that destroy many individual cells without producing a permanent bodily injury, if sufficient time for recovery intervenes between exposures, no one of which is sufficient to overburden the restorative processes. It is on this fact that the commonly accepted ideas regarding tolerance limits of exposure to radiation are based. However, not all types of cells in the human body can co-operate to repair damage. For example, parts of the eye, brain, and most muscular tissues are unable to produce new tissue to replace that which has been destroyed. Great caution must be exercised to prevent exposure of these parts to excessive radiation.

D. GENETIC EFFECTS OF RADIATION

In recent years biological investigations have revealed that certain kinds of injury may occur to cells in the human body that are more complicated than the outright destruction of a cell or of a group of cells. This new information has come from the study of the genetic effects of radiation. These studies show that radiation produces a definite effect on the structure of the chromosomes, the threadlike structures in the cell nuclei that control the characteristics of the cell, and, if it is a cell that later divides, control also the characteristics of its descendants. This control is accomplished by an intricate system of elements, called genes, in the chromosomes, under the assumption that a normal cell has a definite set of chromosomes with an equal number of genes arranged in a particular way in the chromosomes for each type of cell. The effect of the radiation is to alter or destroy either the chromosome, or genes, or both.[1] The result is a mutation in which subsequent cells resulting from division of the affected cell are different from the parent cell. This effect has been proved many times experimentally, using organisms which reproduce rapidly, such as the fruit fly. For man this genetic effect of radiation has two important implications. In one case, cells altered in this way may produce abnormal organs in the body. In the other, if the change has been produced in a germ cell, subsequent offspring may develop abnormally. The importance of these possibilities becomes more prominent in the light of the knowledge that mutational changes are irreversible; there is no recovery. And if a certain dose of radiation will produce a certain percentage increase in mutations, it does not matter whether this dose is administered over a few days or a few years.[2] This is illustrated in Figure 1, which shows that there is no variation in the mutation rate for a given dose administered over a variety of periods.

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[1] G. Failla, *J. Appl. Phys.*, **12**, 279 (1941).

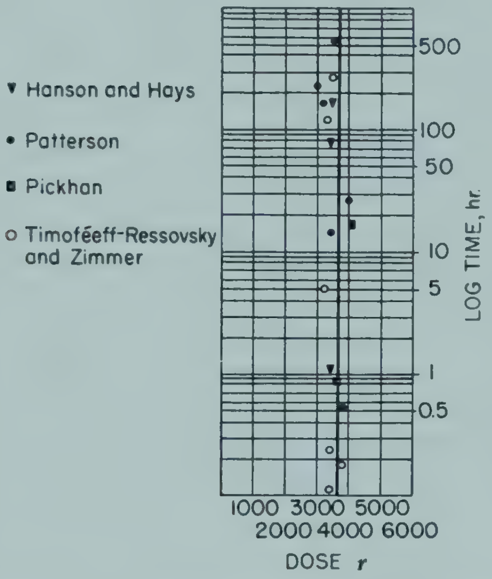

Figure 1. The heavy vertical line, drawn to represent an average of the observations, shows that the mutation rate for *Drosophila melanogaster* is independent of a time factor when a given dose of radiation is administered over various different periods of time.[2] From radiation experiments of the authors listed, the dose of radiation in r that will produce an increase of 10 per cent in the sex-associated mutation rate is calculated and plotted against the time selected for the irradiation. For convenience, a logarithmic time scale is used. These doses fluctuate within statistically expected limits about the value of 3600 r.

An additional fact, which now seems well established, is that the percentage change in mutations is directly proportional to the dose.[2] This is shown in Figure 2. Therefore, taking these two properties together, we see that from the standpoint of genetics the effects of radiation are permanently cumulative. A very weak exposure over several years, therefore, may be as injurious potentially as a large exposure administered at one time.

These facts have an important bearing on tolerance limits of exposures of individuals to radiation, particularly to penetrating radiation, such as x-rays and gamma rays, where germ cells may be affected. It is obvious that as far as man is concerned no information is available, or will become available within present generations, to determine what intensities can be tolerated over a life span without producing an unbearable change in the mutation rate. Such observations are complicated by the fact that most mutations are recessive. Consequently, individuals who escape exhibiting any genetic effects of radiation in their immediate offspring may still be responsible for undesirable hereditary changes in later generations. This arises from the fact that the recessive nature of mutations is such that they ordinarily will not appear in the first succeeding generation. Therefore, the production of normal offspring by individuals exposed to radiation is no proof that genetic injury has not occurred.

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[2] Timoféeff-Ressovsky, Zimmer, and Delbrück, *Nachr. Ges. Biol. Göttingen*, **1**, No. 13 (1935).

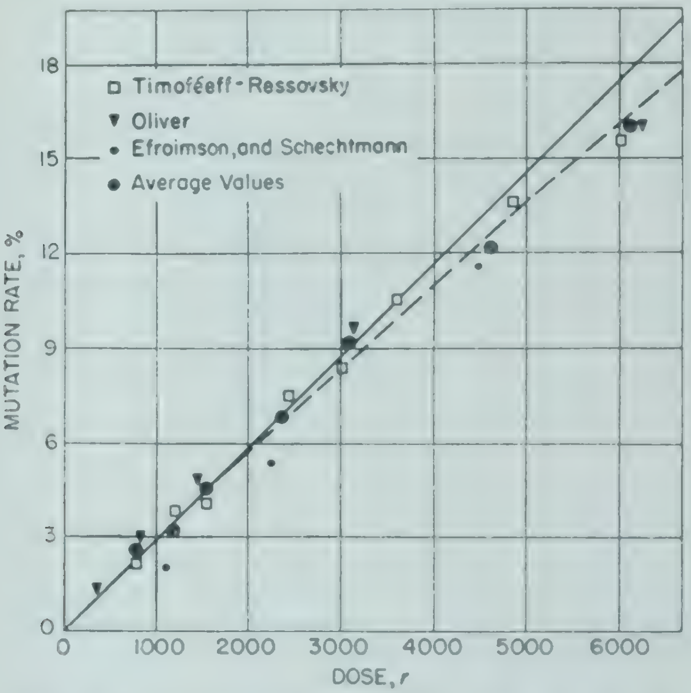

Figure 2. The solid line reveals the direct proportionality of rates of sex-associated mutations in *D. melanogaster* to dose of x-rays. The effect of the saturation curve on the direct proportionality is indicated by the dotted line. The observed points are by different authors as listed.

A certain low mutation rate is normally present in our population. In fact, this is one of the important factors that control the increase or decrease of population. These mutant genes must be eliminated from the population and are, on the average over suitably long periods, at a rate equal to that at which they are produced. The only mode of elimination is by a genetic death. Therefore, any marked increase in this mutation rate induced by exposure of the population to radiation could ultimately exterminate the whole population.

The reason for this can be made clearer from arguments recently outlined by Müller.[3] The most significant fact in a discussion of the effect of mutant genes is that each of these received by an offspring will, on the average, cause a "genetic death" of one descendant. A genetic death may be defined as a death of an individual from genetic causes before reproduction, or a failure to reproduce. It does not need to be a "lethal" gene in the technical sense that it may cause so gross an abnormality as to kill every individual before maturity. Most mutant genes cause such a relatively small impairment in the individuals who carry them that ordinarily it would escape observation. However long the effect may be postponed, the genetic death is inevitable as the only way of eliminating this gene from the population.

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[3] H. J. Müller, *Acta Radiol.*, **41**, 5 (1954).

Most mutant genes are recessive, a few completely so, and if transmitted by only one parent are about one-twentieth to one-thirtieth as effective as when transmitted by both, as deduced from studies on the fruit fly. In spite of the small damage caused in each individual, when summed up over many generations that may occur before elimination of the genes, the damage becomes significant. This situation means that every person is carrying a fairly large number of mutant genes, which are a biological handicap whose effects must be overcome to some extent by improved environmental conditions, and which will ultimately cause genetic death. In fact, the general fitness of an individual, apart from externally produced maladies and the like, may be said to depend directly on the combined action of the mutant genes he carries. The argument that a single mutant gene produces a relatively small, or entirely negligible, effect must be scrutinized carefully. The smaller the damage, the greater the number of generations before elimination. Consequently the total contribution is very large. In fact, it is equal to that of a major "lethal" gene whose effect is almost immediate.

The over-all effects may be reduced by the possibility that a given genetic death is caused by the co-operation of several mutant genes and the presence of adverse environmental conditions. In any case a number of mutant genes will probably be eliminated by each genetic death. Whatever this ratio, there must be the corresponding number of genetic deaths to prevent a continual increase in the number of mutant genes to the point where the whole population is exterminated.

To assess the effect of mutations induced by artificially applied radiation on the population the spontaneous mutation rate must be considered. This is estimated in man at one per 50,000 gametes. It may also be assumed conservatively that there are 15,000 genes per set, which suggests that there are 0.3 mutation present in human gametes of spontaneous origin. In practical words, this means 3 out of every 10 germ cells or eggs would contain somewhere a mutation that had developed in the immediately preceding generation, in addition to all those inherited over many past generations. Combining paternal and maternal contributions, 6 mutant genes must be eliminated for every 10 individuals per generation to maintain equilibrium. Even when also taking into account that it may require three mutations to cause a genetic death, 2 out of every 10 persons in each generation must suffer a genetic death. A simple calculation shows that this demands $2\frac{1}{2}$ children per couple to maintain the population on a genetic argument based solely on spontaneous mutation and ignoring all other causes of genetic death.

The real question then becomes, what effect an increase in mutation by radiation will have on this situation. There are few data for computing the efficiency of radiation in producing mutation but present preliminary investigations show that the increased mutation rate in mice is from 15 to 26×10^{-8} per roentgen per gene or one mutation per roentgen in a given gene among four million gametes. Thus, it can be computed that a dose of 80 roentgens will be equal to the effect of the spontaneous mutation rate. The addition of this radiation per productive lifetime would cause 4 out of 10 individuals to suffer genetic death per generation and each couple escaping would have to produce $3\frac{1}{3}$ children for population equilibrium. Not to be overlooked is the fact that all survivors would carry twice as many mutant genes as a result of the radiation.

These arguments suffice to show that on the basis of population survival the increase in mutation rate becomes a matter for serious consideration. Müller, for example, suggests that an increase of 25 per cent in the mutation rate should be the limit, or 20 roentgens per lifetime per individual. This would require readjustments in our mode of living for ultimate survival that probably could be made. Actually, the use of x-rays for diagnostic purposes has brought the average dose to reproductive organs in this country very near this level already.

To return to the workers with radioactive materials, it is fortunate that they are a relatively small fraction of the population. This fact renders the 0.3 roentgen per week or 400 roentgens in 26 years as permissible from the genetic viewpoint. However, even this can be regarded with equanimity only if there is a corresponding lowering of the general exposure of the population to radiation. At any rate, increase in the use of x-rays may well have a more profound effect on limiting the population than the exposure of a few individuals to the larger lifetime doses encountered under present regulations for handling radioactive materials.

E. VISIBLE EVIDENCE OF INJURY FROM RADIATION

The generally known injurious effects of radiant energy are customarily classified under the type of radiation that produces them. This custom has arisen not so much because the effects are different, since basically they are not, but for the convenience of those dealing primarily with one particular type of radiation. Since this chapter is concerned primarily with hazards which arise in industrial processes where radiation is present, we shall discuss the subject under the headings of gamma rays, x-rays, infrared radiation, and corpuscular radiation. Radioactive poisoning, resulting from taking radioactive substances into the body, is no longer confined to radium poisoning. However, radium dials are still produced and a separate section is devoted to this problem. With the appearance of artificially produced radioisotopes in commerce and the possibilities of industrial applications still largely unexplored, a considerable increase in the industrial use of these products can be expected. Already Co^{60} is replacing radium in radiography and many similar trends will be encountered. Fortunately, the basic principles of protection from injury as well as the nature of the possibilities of injuries are still the same.

The disruptive effects that radiation can produce in living cells result in a great variety of bodily injuries in persons exposed to the radiation. These effects depend on the type of radiation, particularly its penetrating power; on the method of exposure, whether local or over the whole body; and on the parts of the body affected. Injuries range all the way from a slight erythema, such as can result from a small dose of soft x-rays or ultraviolet, to radiation osteitis, which may be followed by crippling bone lesions and osteogenic sarcomas that soon prove fatal. Such injuries may result from large doses of gamma radiation and are also a possible result of severe radioactive poisoning. In many cases of overexposure, anemias occur that may be aplastic or regenerative, depending on the cell groups affected, which, in turn, frequently depend on the type of radiation and its mode of application to the body. Fatal leucopenias also have been observed.

Admittedly, these and other similar symptoms and disabilities are of importance chiefly to the physician who may be called upon to treat a person suspected of suffering from an overexposure. Also, the studies of persons affected by radiation have resulted in valuable additions to the general knowledge of bodily functions. They are cited here primarily to indicate the severity of injury that may result from injudicious exposures of the body to radiant energy. In most situations, ample information is now available so that protective measures can be set up to prevent all but the foolhardy, or grossly ignorant, from suffering any of the more serious consequences of overexposure. It will be our aim to point out these protective procedures in the course of the detailed discussions of the various industrial hazards that involve radiant energy.

II. Penetrating Ionizing Radiation

A. TYPES OF EXPOSURES AND INJURIES

The penetrating radiations typified by x-rays and gamma rays, through the ionizing effects of their secondary corpuscular radiation, produce similar effects on the human body. The distinction between these radiations is purely arbitrary since gamma rays may now be produced by the same mechanism as was formerly used to produce x-rays. These penetrating radiations, when compared with other forms of radiant energy, possess the distinguishing property of being able to produce effects throughout the whole body at one time. This ability accrues from the low coefficient of absorption which permits the radiation to pass entirely through any part of the body with only a moderate diminution of intensity. Naturally, it is still possible to expose only a part of the body, as by extending the hand into a well-defined beam of radiation, and in practice local overexposures may readily occur. However, such local exposures are much more apt to be accidental, or the result of carelessness, whereas the whole-body exposure originates from the difficulty of screening this type of radiation. Consequently, workers engaged in the application of x-rays and gamma rays in industrial plants are subject to both types of exposure.

B. LATENT PERIOD

From our introductory discussion of current ideas as to how radiation can produce injury to living tissue, it is apparent that the full effects of irradiation will not be manifest at once. The destruction of cells in a complicated assembly such as human tissues will set in motion a train of events that may reach a culmination weeks or months after the exposure. Since not every cell in the tissue affected is destroyed by radiation, as would be likely to be the case in a burn produced by excessive temperature, the tissue begins to exhibit the deficiencies resulting from the occasional destruction of isolated cells only after a period of development during which the injured or obliterated cells obstruct normal growth. Consequently, one of the most striking characteristics of injuries arising from penetrating radiation is the latent period that always intervenes between the exposure and the visible manifestations of its effects. We are all familiar with the same general process in ordinary sunburn, in which the burn develops several hours after exposure. In the case of gamma rays, this latent period extends to several days, even when the effect produced is in surface tissues, as in an erythema, and many effects may develop much later. This is particularly true of malignancies that originate from exposure to radiation.

Because of this latent period there is no warning of injury at the time of exposure, even for local injuries that are severe enough to develop into painful and crippling burns. It is only by habitual regard for definitely safe procedures that persons working with sources of penetrating radiation, such as accelerators or radioisotopes, can escape injuries of various kinds. These injuries may be a slight or severe erythema and, from greater exposures, a deep deterioration of underlying tissues causing a permanent deformity. In another category are injuries, such as keratoses, malignant growths, and even deep-seated cancers, that develop over a period of years and do not produce detectable effects, in some instances, until they have reached an advanced stage. We also know that large doses of penetrating radiation, whether received as a single massive dose or distributed over a long period, will produce noticeable disturbances in the blood count. If the dose is large enough, anemia or leucopenia may occur almost immediately. Either disease can reach a fatal stage unless the exposure is interrupted and restorative measures applied in time.

C. TOLERANCE DOSE

Whereas local injuries from penetrating radiation can be avoided by careful habits of work and suitable protective screens, the prevention of excessive exposure over the whole body must be based on a knowledge of the dosage that will not produce detectable injury. Admittedly, the information on this subject is somewhat scanty and is based entirely on accumulated experience over the past fifty years.

The question of permissible levels of radiation has received a great deal of attention since the development of nuclear reactors with their ability to produce enormous amounts of radioactivity. One result has been to modify the use of the roentgen to take account of the variation in the biological effects of different types of radiation. This has also led to the definition of a companion unit called the "r.e.p." (roentgen-equivalent-physical) defined as the amount of radiation that, on absorption in soft tissues, delivers 93 ergs per gram of tissue. This arises from the fact that the roentgen, defined as the amount of x-radiation or gamma-radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 electrostatic unit of electricity of either sign, delivers 83 ergs per gram of air. This same radiation has been found to deliver 90 to 110 ergs per gram in various tissues. The use of the r.e.p. to replace the roentgen has the practical effect of slightly reducing the tolerance limits, as stated in the same number of roentgens.

There are small divergences in the recommended maximum limits of radiation exposure among those customarily dealing with large-scale operations in this field. Perhaps the most generally accepted are those recommended by the International Commission on Radiation Protection in 1950, summarized in Table 1.

TABLE 1

Maximum Permissible Radiation Exposures[a]

		No. of r.e.p. per week		
		At any point in body	In basal layer of epidermis	
Radiation	RBE		Entire body	Hands
X- and γ-rays	1	0.3	0.5	1.5
β-rays	1	0.3	0.5	1.5
Protons	10	0.03	0.05	0.15
α-rays	20	0.015	0.025	0.075
Fast neutrons	10	0.03	0.05	0.15
Thermal neutrons	5	0.06	0.1	0.3

[a] Because of changes in recommendations resulting from new information on potential damage from radiation, frequent revisions of these data can be expected. These revisions are usually announced in journals in the field of radiology and radiation protection.

The relative biological effectiveness, RBE, in the second column is merely a rough estimate of the relative amount of damage which one roentgen of the radiation will produce in tissue. The value for thermal neutrons is particularly open to question. This estimate of RBE as shown by the numerical values controls the recommended exposure, relative to gamma-rays in each case.

In regard to ingestion or inhalation of radioactive substances, there is no simple way to arrive at a maximum safe quantity to be carried in the body. For most radioactive isotopes there is equally no convenient satisfactory way of measuring quantities of activity in the living body at or near the estimated safe level. Therefore reliance must be placed on maintaining concentrations in air and water used by persons, where measurements can be made, below levels which have been recommended by the National Radiation Committee (Handbook 52, National Bureau of Standards). These concentrations have been deduced from estimates of amounts of individual radioisotopes that could be expected to yield a dose producing the effect of 0.3 roentgen per week when absorbed in the organ for which the isotope has a chemical affinity. A few typical examples of these recommendations are given in Table 2.

TABLE 2

Maximum Permissible Concentrations of Radioactive Isotopes in Human Body and in Air and Water for Human Consumption

Isotope	Critical organ	Microcuries in total body	Microcuries per cubic centimeter	
			Water	Air
C^{14}	Fat	250	3×10^{-3}	1×10^{-6}
C^{14}	Bone	1500	4×10^{-3}	5×10^{-7}
Na^{24}	Whole body	15	8×10^{-3}	2×10^{-6}
P^{32}	Bone	10	2×10^{-4}	1×10^{-7}
Ca^{45}	Bone	65	5×10^{-4}	3×10^{-8}
Fe^{55}	Blood	1000	4×10^{-3}	6×10^{-7}
Zn^{65}	Bone	430	6×10^{-2}	2×10^{-6}
Sr^{89}	Bone	2	7×10^{-5}	2×10^{-8}
I^{131}	Thyroid	0.3	3×10^{-5}	3×10^{-9}

D. HEALTH PHYSICIST

An entirely new profession has been brought into existence by the large-scale operations involving radioactivity that have resulted from the development of the atom bomb. Members of this group, known as health physicists, are individuals trained in physics who have gained experience in making the measurements of radioactivity required to insure the safety of employees. This development further emphasizes the nature of the preventive measures that are essential in dealing with radiation. The only road to safety is elimination of the possibility of overexposure, since no satisfactory treatment of radiation injury, particularly in severe cases, is available at present.

The duties of the health physicist include recommendations for procedures that will insure freedom from injury to the participants, both in experimental investigations and in routine operations. Once the operation is established, he also is responsible for ascertaining that the recommendations were properly followed and that they did result in safe conditions. He also takes care of all routine monitoring of areas containing radioactive materials to detect any new hazards or failures to comply with regulations. He reads personnel meters and keeps records of the results. In case of an accident he must supervise the cleaning operations and determine when the area is again suitable for occupation.

The health physics functions may be carried on by a single individual or may require a staff of a hundred or more depending, of course, on the scale of operations. In very small laboratories these duties may continue, as before World War II, to be taken care of by the investigators themselves. Even at best this is not a reliable procedure and most overexposures to radiation in laboratories have occurred under such an arrangement. In the larger laboratories the health physics staff will not only be expected to calibrate, adjust and repair the measuring instruments but frequently will be called on to develop new instruments, or improved models of those existing, to meet special demands.

An important aspect of the health physics work is the accumulation of records of the conditions of employment of each individual as regards exposure to radiation. The value of these records goes well beyond the immediate purpose of ascertaining that satisfactory conditions have been maintained and of detecting deviations in the incipient stages. The general public has become well aware of the possible effects of radiation, and there are always a few individuals who will be prone to attribute almost any malady, particularly if it is of a malignant nature, to the fact that they work or have worked where radioactive materials have been handled. This occasionally leads to exorbitant claims and even suits at law to recover imagined damages. It could well happen in a large institution that the possibility of proving absence of undue exposure to radiation, in connection with such claims, would save the whole cost of the health protection service.

The importance of the health physics department in large-scale operations involving large sources of radioactivity is such that great care must be used in selecting the men who are to operate it, particularly at supervisory levels. While a number of individuals have been trained in laboratories under the Atomic Energy Commission, the demands of these organizations for services that these men can perform are increasing. Because the problems with which they have to deal primarily concern the measurement of the different types of radiation under various conditions, the fundamental requirement is that they should have a firm grasp of the principles of the physics of radiation and its interaction with matter. Most of the other desirable attributes can be developed through training experience in a well-organized health physics department. It must be remembered that these men must not only devise safe procedures but also provide methods that do not make the desired operations all but impossible to perform or prohibitive in cost. Consequently, an industrial hygienist would be competent in this position only if he had a thorough training in radiation physics.

The health physicist or other persons charged with supervising the safety of an area in which operations involving the use of radiation are performed require a number of instruments and devices for measuring radiation. A description of the more important of these and their principles of operation will be found in Volume III of this book.

E. BLOOD COUNTS AS INDEX OF INJURY

In spite of all due caution in manipulations and proper measurements to insure that the tolerance dose is not exceeded, it is conceivable that some individuals may be more than ordinarily sensitive to radiation, or may accidentally receive excessive exposures not detected by metering badges supposedly worn by all personnel in radiation areas. The best check on such possibilities known at present is the use of regular blood counts. Although such observations are not satisfactory for revealing moderate overexposures, it is well established that strong irradiation by penetrating radiation causes characteristic changes in the blood picture. The real difficulty is that these changes frequently become definitely recognizable only after the damage has been done. Furthermore, the results of the counts, which always should be made by the same technician for each person under observation, and under similar conditions, should be interpreted by an experienced hematologist. These counts should include: hemoglobin test, red, white, and differential counts, including the percentages of polymorphonuclear cells, small and large lymphocytes (separately), eosinophiles and basophiles. Blood platelet, sedimentation, and coagulation tests also are of value.

A guide in determining departures from a normal blood count is provided by Table 3 as given by Goodfellow,[4] who has investigated the effects on the blood count of exposures to gamma rays. He finds that the only sign of overexposure common to all workers is a leucopenia, due to a reduction of circulating neutrophiles. There is evidence that different individuals vary in susceptibility to the effects of irradiation. Those who are more sensitive exhibit an absolute lymphocytosis with an absolute leucopenia as the first sign of overexposure. Others, less sensitive, under the same conditions show a lymphocythemia with a monocytosis. Eosinophilia is frequently seen as a result of overexposure, and abnormal or embryonic leucocytes have been observed. Goodfellow states that vacations of less than four weeks do not appear to be of value in restoring leucocyte counts to normal.

F. RADIOISOTOPES

In the last ten years the use of artificially produced radioisotopes of many common elements has given rise to new industrial problems of protection, which may be expected to grow in magnitude and complexity. Although the principles of health protection remain the same as in the days when radium and its decay products were about the only sources of radioactivity, they must now be applied to a greater variety of situations. There are available now, also, sources of many times the intensity of former preparations of radium. At the same time many types

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[4] D. R. Goodfellow, *Brit. J. Radiol.*, **8**, 669, 752 (1936).

TABLE 3
Typical Blood Counts as Reported by Various Authorities

Type of cell	Mottram	Schilling	Dyke	Shaw	Emerson	Simpson	Simpson: Widest variations observed	Taylor, *Practice of Medicine:* Accepted normal limits (in morning)
Total W.B.C.s								
Max.	—	8,000	8,500	9,650	8,000	11,200	18,100	9,000
Min.	—	6,000	5,500	3,200	6,000	5,100	2,800	4,000
Mean	—	—	—	5,987	—	—	—	—
Neutrophiles								
Max.	12,000	—	75%	69.8%	70%	8,920	13,100	5,000
Min.	3,000	—	60%	37.0%	63%	2,920	1,600	2,500
Mean	—	67%	—	53.2%	—	—	—	—
Lymphocytes								
Max.	6,000	—	40%	51.2%	30%	2,440	4,040	3,000
Min.	1,500	—	25%	22.6%	20%	1,010	820	1,500
Mean	—	23%	—	36.8%	—	—	—	—
Monocytes								
Max.	—	—	7%	10.0%	10%	—	—	600
Min.	—	—	2%	3.0%	—	—	—	20
Mean	—	6%	—	6.7%	—	—	—	—
Eosinophiles								
Max.	—	—	2%	6.4%	2%	—	—	400
Min.	—	—	0%	0.0%	—	—	—	20
Mean	—	3%	—	2.5%	—	—	—	—
Basophiles								
Max.	—	—	1%	2.0%	0.5%	—	—	10
Min.	—	—	0%	0.0%	—	—	—	0
Mean	—	1%	—	0.7%	—	—	—	—

of work involving radioactivity, for example, investigations with radioactive tracers, conveniently use relatively weak sources.

In a general survey of precautions required it is convenient to divide the various operations into several ranges of intensity. At present the commonly used unit for measurement of the quantity of radioactivity is the curie, defined as that amount of any radioisotope which is undergoing 3.7×10^{10} disintegrations per second. This automatically defines a different number of atoms for each radionuclide as a unit quantity, through the relation $dN/dt = -\lambda N$, where N is the number of atoms present at the moment of measurement, dN/dt is the rate of disintegration, and λ is the disintegration constant. N for one curie of a nuclide is then defined by $3.7 \times 10^{10} = -\lambda N$; and, since λ is different for each nuclide, N will also be different. However, for a given nuclide the radiation emitted is proportional to the rate of disintegration and a measurement in curies yields a value that will give the intensity of radiation if the intensity per curie is known. In view of the fact that the emitted radiation is also different in character for each nuclide the radiation per curie will vary from nuclide to nuclide.

Based on earlier experiences with radioactivity, the curie is a relatively large unit since, for example, a curie of radium is almost exactly one gram of radium. Consequently, for many purposes it is still preferable to use smaller subdivisions of this unit. These are: the *millicurie* (10^{-3} curie) with $dN/dt = 3.7 \times 10^7$ disintegrations per second; the *microcurie* (10^{-6} curie) with $dN/dt = 3.7 \times 10^4$ disintegrations per second; the *millimicrocurie* (10^{-9} curie) with $dN/dt = 37$ disintegrations per second. This last unit is approaching the limit of detection for many of the less sensitive instruments used in measurement of radioactivity but can readily be measured with Geiger-Müller and scintillation counters and the more sensitive ionization chambers.

In general, it is safe to say that operations involving quantities of radioactivity of the order of millimicrocuries offer no hazards from radiation. Indeed, to make accurate measurements in this range such caution is required to prevent contamination of utensils and instruments that scrupulous care and cleanliness are automatically imposed, which insure that the active material is confined to its proper place. The intensities of the radiations at usual distances are negligible from the standpoint of biological injury. Even at the microcurie level the proper precautions in handling ordinary chemical substances generally will suffice to provide adequate protection from radiation. Depending on the type of radiation emitted, whether alpha, beta, or gamma, and its energy, forceps or tongs should be used to handle the small containers in which such preparations are usually contained. Moderate shielding may be desirable to screen off beta and gamma rays. The degree of care required in making use of general precautions will depend greatly on the volume of work, and particularly on whether the occupation is continuous or intermittent.

At this level the chance of "poisoning" begins to appear. Under careless management injurious quantities of radioactivity could be inhaled or ingested, so that regulations commonly in effect in radium dial painting plants must be invoked. Some radioisotopes are more dangerous than others because of their tendency to accumulate in particular organs of the body. If the microcurie samples originate from much more intense sources as aliquots for measurement it is obvious that greater care is required to prevent gross contamination of the measuring room with possible hazards to health.

One convenient means for detecting deviation in procedure is the regular use of radiation meters, of the ionization or photographic type, worn continuously during working hours. Survey meters also should be used frequently on tables, floors, and equipment as additional safeguards. Where a number of different isotopes are in use it is advisable for these survey meters to be able to detect alpha and beta as well as gamma radiation. In some installations regular measurements of radioactivity of the workroom air also may be desirable.

When quantities of the order of millicuries or greater are handled, very rigid restrictions must be placed on the operations to insure safety from radiation. Also, more elaborate tongs, special radiation shields of lead or other dense material, and special ventilation are required. Where chemical operations are performed, hoods designed for the work, dry boxes, and other means of confining the radioactive material to desired locations must be used. This is also the level at which the worker must wear coveralls, designed for ease of laundering, and available for inspection and measurement of radioactivity after use.

At source strengths of the order of a curie and above, all precautions become more complicated, particularly those of shielding and remote control. Chemical operations must be manipulated from the outside of heavy concrete cubicles containing the active material, by the aid of remote control devices and periscopes or very thick transparent shields. Fortunately, work at this level can be expected to be confined in general to a few laboratories, such as those operated for the Atomic Energy Commission, where special procedures have been developed through experience and measurement for each set of conditions encountered.

G. PROTECTION FROM GAMMA RAYS

1. Pre-employment Examination

The first rule for safeguarding employees who handle radioactive material is that only those who have been found by thorough medical examination to be in excellent health should be employed. This precaution will reduce the possibility of assigning exposure to gamma rays as a cause of some ailment already in progress before any exposure. It can also eliminate persons with abnormalities, such as unusual blood picture, chronic anemia, and so forth. In this way, the number of individuals unusually susceptible to radiation injury will be reduced. Finally, it establishes a reference for future medical examinations of the individual, permitting changes in health and symptoms that may occur to be observed and recorded.

It is also important to explain to a prospective employee for work with radioactive substances the nature of the proposed work, the type of hazards involved, and the details of the protective measures and regulations, especially those that apply with particular emphasis to the job in question.

2. Protection of Personnel

The protection of employees working with radioisotopes emitting gamma radiation involves the prevention of overexposure, both locally and over the entire body. The most convenient way to achieve this is by taking advantage of the inverse-square law, by keeping the personnel at adequate distances from the sources of radiation. The importance of distance from the source is illustrated by

Table 4, taken from Handbook H-23 of the National Bureau of Standards, *Radium Protection*, which shows permissible daily exposures (based on the now discarded tolerance level of 0.1 *r* per 8-hour day) with contingent safe distances of a technician during these exposures.

TABLE 4

Safe Working Distances from Radium

Total daily exposure (mg.-hr.)	Safe distance		Total daily exposure (mg.-hr.)	Safe distance	
	Meters	Feet		Meters	Feet
100	1	3	800	2.5	8
200	1.5	4	1600	3.5	11
400	2	6	3200	5.	15

The next factor in order of importance is reduction of the time of exposure. Therefore, provisions should be made to permit all operations involving unusual levels of gamma ray intensity to be carried out in the shortest time consistent with the nature of the operation and with the personnel as far from the radioactive material as can be arranged. Under no circumstances should sources of the order of a millicurie or greater come into contact with any part of the worker's body, especially the fingers. It should be obvious that technicians should not remain in the immediate vicinity of an unshielded source longer than necessary, a precaution that also applies to those not directly concerned with the work in hand. This is particularly important in gamma ray radiography where very strong sources are often used to reduce the time required to obtain a satisfactory negative.

Finally, consideration should be given to protective screens of dense material having a high coefficient of absorption for gamma rays. This material may be lead, iron, or concrete. Screens must be provided whenever operations with strong sources, millicurie level and above, are to be carried out at short range. The thickness of the screens should be adequate to reduce the radiation to a level well below the average tolerance for continuous exposure. Where viewing the source is essential to the operation, thick transparent screens or periscopes must be provided to make the screening complete.

All employees in the radiation area, or having access to it, should wear personnel radiation meters continuously, and these should be collected and read at the end of each day by someone in charge of radiation safety. This assures early detection of any violations of regulations or accidental overexposures. The record of these readings is valuable also as proof of absence of serious overexposures.

Regular medical examinations should be given individuals engaged in this work. The examination should include a blood count as well as a careful check of each of the known possible symptoms of overexposure to radiation. In particular, an examination for evidences of injury to fingers should be made. The frequency with which medical examinations should be made depends somewhat on the conditions of work. Where gamma ray sources of the order of a curie or more are involved, an examination every month would seem to be required. If operations are substantially below this level, and particularly if possibilities of exposure to radiation are infrequent, an examination every six months might be adequate.

3. Storage of Radioactive Sources

The storage of radioactive sources, emitting penetrating gamma radiation with energies of the order of 1 Mev. or greater, presents something of a problem, particularly where large amounts are involved. Industrial radiography is an example. In general, the inverse-square law provides the most economical and effective means of solving this problem. However, a certain amount of lead, or its equivalent, shielding is required to permit approach to the storage vault and to protect those who may require to be temporarily in its vicinity. Where the occupancy of the space about the vault can be rigidly controlled, the thickness of the shielding in any particular direction will depend, for a given amount of radioactive material, upon the distance to the person to be protected, the period of time for which protection is required, and the effect that the required protective screen may have on the intensity of the radiation in other directions where protection may be required. In other words, the scattered radiation must be taken into account and in some cases this can be done only by actual measurement. In any case the combined protective arrangements must reduce the whole body exposure to the tolerance dose.

Storage vaults should be designed with an interior cavity no larger than required to accommodate the sources to be stored. Not only is this more economical but, by reducing the size of the exterior, it also reduces the amount of scattered radiation in the vicinity. When material other than lead is used for this vault, the lead equivalent (see Table 5) must be known under conditions similar to those in which the material is to be used. In general, the lead equivalent for gamma rays can be computed by multiplying the thickness of the material by the ratio of its density to that of lead. In computing required thicknesses, it is advisable to increase the thickness of material by about 50 per cent of the value obtained in the above computation.

When designing storage vaults for a number of sources it is desirable to provide separate lead screening for individual preparations. This reduces the exposure of the technician who must remove sources from the vault. It is equally important to adopt a convenient, methodical arrangement for storage so that the time required to select and remove a source is reduced to a minimum. Identifying numbers, readily legible at some distance, illustrate one method of expediting the selection of a preparation. Another suggestion is to code with distinctive colors the sources themselves to permit instant identification. In no case should the dose received during the selection and removal of preparations exceed a small fraction of the permissible daily dose in routine operations.

For large sources it is frequently convenient to design the storage vault as a part of the apparatus in which the source is used. This is accomplished by providing a shielded well into which the source can be lowered for storage and from which it is raised into position for work by a remote control mechanism. This provides for a minimum exposure of the technician, who never needs to go near the source. If it is not convenient to have a plug follow the source into the well hole, the intensity of the radiation directly above can be reduced by filling the well with a sufficient depth of heavy oil or other suitable liquid.

4. Manipulation

It is difficult to enumerate, within the space available, the various accessories and arrangements that can be employed to reduce the exposure of the technician handling radioactive sources. A great variety of remote control devices have been used to place sources in desired positions while the operator remains at a safe distance. The simplest are often long cords used with guides to pull a source into place or to remove it. The more complicated are huge machines designed to place a source accurately into a close-fitting receptacle. These devices can be so well controlled that they can be used to lift a glass beaker and pour its contents into another container. In between these examples are tongs and forceps of various sizes and degrees of complexity. The important point is to make certain that such arrangements are used wherever desirable. However, remote control devices should not be so awkward to manipulate that they greatly increase the exposure time and thereby defeat their purpose. Fortunately, it is possible to check by actual measurement the exposure received during a particular operation; thus, various methods can be compared with respect to exposure.

It should never be assumed that rules of procedure and specific instructions to technicians and assistants are sufficient to preclude possibility of injury. Wherever large amounts of radioactive material of the order of millicuries or greater are handled, there may be situations that require excessive exposures of short duration, and these may occur with unexpected frequency. Therefore, operators should be under constant supervision to control the number of excessive exposures, that is, exposures above the average tolerance level for continuous exposure during the working day.

5. Waste Disposal and Removal of Radioactive Contamination

In some uses of radioisotopes certain fractions of the material are discarded in the course of the normal operation. Also, unused portions of short-lived radioisotopes may be thrown away at the end of an operation. Finally, accidents may happen in which radioactive material is spilled in such a way as to constitute a serious hazard to health unless it is promptly removed and disposed of so as to offer no further possibility of human contact with it. The seriousness of these situations increases rapidly with increase in the amount of radioactive material involved.

The utmost caution should be used to prevent radioactive contamination of the skin or clothing of persons. This applies to accidents as well as to routine operations. It requires careful washing and monitoring of every individual leaving an area where contamination by radioactive materials is possible. Contamination can be removed from hands by thorough washing with soap and water repeatedly until measurements show that the amount has been reduced to a satisfactorily low level. In extreme cases a dilute acid rinse may be required.

Where protective garments are too heavily contaminated to permit removal by laundering in special laundry equipment, they should be discarded in the same way as other radioactive wastes. In no case should garments be sent to commercial laundries until preliminary treatment has reduced the contamination below tolerance levels. In dealing with problems of this kind the half-life of the radioactive material must be taken into consideration. If this half-life is a few days, as in the case of I^{131}, the contamination can be removed by storage for a few weeks. On the other hand, if the half-life is of the order of a year or more, the garments must be discarded if the contamination cannot be removed. As a rough guide to permissible contamination a Geiger-Müller counter having a window 2 square inches in area will give a response of about 1000 counts per minute when placed as close as possible to the contaminated surface. If low energy radiations are present the window of the counter should have a thickness corresponding to two to three milligrams per square centimeter.

In operations involving the discard of amounts of radioisotopes of the order of a millicurie or greater, and in decontamination operations following an accident involving similar amounts, wash solutions should not be permitted to drain into the sewer but into suitable receptacles for ultimate disposal.

The ultimate disposal of radioactive wastes of the order of a millicurie or more at a time depends on facilities available as well as on the chemical nature of the radioisotope and its half-life. Where problems of this kind are encountered routinely it has been the practice in some places to assemble this discarded material periodically, encase it in concrete in oil drums, and drop it at sea. In other places "burying grounds" for material have been provided at considerable depths in an area remote from human habitation. Various organizations have this problem under scrutiny and from time to time make recommendations based on study and experience. The fundamental principle on which all such recommendations are based is the preclusion of any future possible contact with humans in a manner that might prove injurious. Among the institutions interested in these problems are the Public Health Service and the National Bureau of Standards as well as the Atomic Energy Commission. A list of handbooks that have been prepared by the National Committee on Radiation Protection appears at the end of this chapter. Many specific details, too lengthy to include here, will be found in these handbooks.

6. *Transportation by Common Carrier*

The shipment of radioisotopes by rail or air is now controlled by the Interstate Commerce Commission, which has authority to enforce its regulations by the imposition of penalties for violations. This matter was taken under their supervision in 1947 when it had become apparent that the large volume of artificial radioisotopes currently requiring shipment demanded more adequate control than had existed previously.

The problem of shipping radioisotopes is complicated by the fact that undeveloped photographic film is also shipped by common carrier and is readily damaged by very small exposures to penetrating radiation. This problem had already been encountered with shipments of radium. The solution consisted in devising a method of packing and disposition of radioactive material in transit that would reduce the level of radiation at any point occupied by photographic film below that at which practical damage could occur. All packages of radioisotopes must be labelled in a prescribed manner showing the nature of the contents and the amount of emergent radiation.

These regulations are available from the Bureau of Explosives, 30 Vesey Street, New York 7, N. Y., as Supplement No. 10 to ICC 4670. Since all shipments of radioisotopes must comply with these regulations, it is incumbent on prospective shippers to become thoroughly familiar with them. An explanatory monograph has been prepared by Robley D. Evans, Chairman of the Subcommittee on Shipment of Radioactive Substances of the Committee on Nuclear Science of the National Research Council. This monograph is obtainable from the National Research Council, 2101 Constitution Avenue N. W., Washington 25, D. C., as Publication 205.

H. PROTECTION FROM X-RAYS

1. *Special Features*

Although the problem of protecting personnel from x-radiation is similar in many respects to that of protecting them from gamma rays, actual conditions frequently are very different. Physiological effects to be expected are much the same, and tolerance doses are measured in the same unit. Where the intensities and energies of the radiations differ considerably from those usually encountered with gamma rays from radioisotopes or accelerators, the details of protective arrangements must be modified to correspond.

The source of x-rays, the x-ray tube, because of its more extensive volume and the necessity of providing electrical conductors, increases the difficulty of shielding. Such bulky sources also scatter diffuse radiation in the vicinity, an effect that is more pronounced the higher the intensities of radiation generated.

In dealing with the protection of personnel engaged in this work, the electrical hazard from high potentials also must be discussed since this is about as frequent a source of injury as exposure to radiation.

2. Protection from Electric Shock

For industrial applications of x-rays, this problem can be divided into twc general cases depending on the two types of generating equipment commonly used. One is the portable or semiportable unit in which all parts are built into a single enclosure and shielded electrically. In the use of this unit, the operator cannot take advantage of the electrical protection offered by insulating the surface of floors and surrounding objects. Rubber shoes and gloves may reduce danger of shock to some extent, but the only sure protection from shock is a continuous grounded metal enclosure for all parts of the unit, so that it is quite impossible for the operator to touch any part that is not at ground potential. This includes high voltage and low voltage cables, control panels, and all other exterior parts. The electrical bonds between these parts not only must insure permanent electrical union of the parts, but also should be substantial mechanically. In some cases, a single heavy cable connecting some part of the grounded system to a permanently earthed point, such as a water pipe, may be sufficient. However, in some types of equipment, high frequency currents may develop that will cause sparks to ground unless several grounds are used at frequent intervals.

The second type of x-ray generating equipment, which is less common, is built into one or more rooms, requiring all work to be brought to the x-ray tube. The same general rules apply to this equipment, but greater precautions must be used where parts cannot be permanently shielded. If the high voltage is generated in a separate room, provision must be made so that it is not possible to enter the tube room with the generator in operation. Also, a cut-off switch should be provided near the tube to prevent energizing the high-voltage transformer when a workman is in the tube room. If high voltage conductors are not enclosed in grounded shields, they must be at a sufficient distance from all points where persons may normally walk that there is no possibility of injury from a spark. This distance is about $7^1/_2$ feet for voltages below 225 kilovolts and correspondingly greater for higher voltages. Suitable signal lights are recommended to indicate various conditions of the generating equipment and should be so arranged as to avoid misinterpretation. In all cases a pilot light should indicate when the main switch controlling the generator is closed.

Overload circuit breakers of a sensitive and quick-acting type should be included in the primary circuit and adjusted to throw at 20 per cent above normal load.

The control panel of all x-ray generators should be located so that the x-ray tube is completely in view of the operator. This may be accomplished by some type of indirect viewing device to screen the operator from scattered radiation;

or a suitable filter, transparent to visible light but sufficiently opaque to x-rays, may be placed in the line of sight.

Since many electrical shocks prove fatal only because of failure to apply restorative treatment at once, it is imperative that all personnel concerned with the operation of an x-ray unit be familiar with the methods of artificial respiration and the aftertreatment of a revived person. This familiarity should be the result of actual training. Although a physician should be summoned at once, the restorative measures should be started immediately, since the chances of a successful outcome are greatly increased by appropriate procedures in the first few minutes after the shock.

3. Shielding Materials for Protection against X-rays and Gamma Rays

Singer, Wyckoff, and Day[5] have made careful measurements on the relative thicknesses of lead, concrete, and steel required for protection from a narrow beam of x-rays generated by potentials from 200 to 1400 kv. They found that for 1400 kv. the ratio of thickness of concrete to the thickness of lead to produce the same attenuation is 5.5, a relation that is strictly linear from 10 to 75 cm. of concrete. At 1000 kv. this ratio is 6.4 for a range of thickness of concrete from 10 to 65 cm., with small departure from linearity in the region between 10 and 20 cm. At 600 kv. this ratio has increased to 10 for a range of 10 to 50 cm. of concrete, and at 200 kv. the ratio is about 50 between 10 and 25 cm. of concrete.

The ratio of thickness of steel to thickness of lead was found to vary from about 13.5 for 200 kv. radiation to about 1.5 for 1400 kv. radiation.

For many purposes, lead is most suitable for use in screening x-rays. In some situations, however, it is more convenient and economical to use other materials, including the structural materials of the building itself. One of the most common is concrete, carefully compounded and poured to prevent formation of air spaces. It is usual to specify lead equivalence of such materials to indicate their relative efficiency as a screen. The protection coefficient, which is the ratio of the thickness of lead to the thickness of material that absorbs a given beam of radiation to the same extent, is more convenient for calculation. The lead equivalent for a material is the thickness of lead found by multiplying a given thickness of the material by its protection coefficient. Values for protection coefficients, taken from data by Kaye[6] and his associates, are given in Table 5.

When dealing with x-radiation generated at potentials above 200 kv., scattering of the radiation is appreciable. At about 500 kv. the scattered radiation has a hardness of about one half that voltage, and for 1000 kv. the value is one third. Therefore, in computing thicknesses of shielding material where scattered radiation may be involved, the absorption coefficients for x-rays of voltages corresponding to those for the scattered radiation must be used.

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[5] G. Singer, H. O. Wyckoff, and F. H. Day, *J. Research Natl. Bur. Standards*, **38**, [illegible] (1947).

[6] G. Kaye, W. Binks, and G. E. Bell, *Brit. J. Radiol.*, **11**, 676 (1938).

TABLE 5

Protection Coefficients (with Reference to Lead) for Some Structural Materials

Building material	X-rays				Gamma rays
	150 kv.	200 kv.	300 kv.	400 kv.	
Iron	0.08	0.07	0.11	0.14	0.47
Concrete	0.013	0.014	0.026	0.033	0.14
Brick	0.0009	0.009	0.015	0.019	0.08

4. Shield of the X-ray Tube

The x-ray tube in all cases should be completely surrounded, except for the opening for the emergent beam, with protective material of adequate thickness to reduce the radiation to tolerance level or below at all points outside the beam likely to be occupied by personnel. There has been a decided tendency in recent years on the part of manufacturers to make this shield an integral part of the tube structure, or support. However, it is desirable to make certain that the screening is adequate in all such types of tubes. Table 6 shows minimum lead thicknesses required for shields for a few typical voltages applied to the x-ray tube. These values are only approximate to illustrate the nature of the problem. In any actual installation the effectiveness of the shield should be tested by measurements of the dosage in roentgens at appropriate locations in the vicinity of the tube. For safest operation, personnel should never remain unnecessarily in the vicinity of an x-ray tube in operation, even though measurements have shown that the shielding meets the usual requirements. In most industrial applications there is no reason for anyone to be near the x-ray tube during an exposure.

TABLE 6

Approximate Lead Thickness Required to Protect Individuals from X-rays Generated by Various Voltages

X-rays generated by peak voltages not in excess of (kv.)	Minimum required thickness of lead barrier (mm.)	X-rays generated by peak voltages not in excess of (kv.)	Minimum required thickness of lead barrier (mm.)
75	1.0	400	15.0
100	1.5	500	22.0
125	2.0	600	34.0
150	2.5	800	40.0
175	3.0	1000	80.0
200	4.0	2000	175.0
225	5.0	5000	290.0
300	9.0		

5. Screening Complete Rooms

In some situations it is desirable to line with lead, or equivalent materials, a complete room in which an x-ray tube is located to provide protection, in adjacent rooms, from the scattered radiation. Where this is done, the protective material should be joined in a lapped joint; and all perforations, such as nail holes, should be adequately covered with lead. Lap joints that leave no unobstructed path for x-rays also should be provided at the doors of such a room. The thickness of this material should conform approximately to the figures given in Table 6.

6. Ventilation

In x-ray installations where corona discharge may generate noxious gases, such as oxides of nitrogen and ozone, forced ventilation is required. Such a condition exists where high voltage conductors are exposed in the air. Under usual conditions, the rate of change of air ordinarily recommended for general ventilation, four or five changes per hour, will be sufficient to reduce these gases below the level where any discomfort or harmful exposure will result.

7. Special Conditions

It is impossible to suggest, within a reasonable space, rules that will apply to all conditions. As conditions change, either regarding tolerance levels or type of generating equipment, the National Radiation Protection Committee issues handbooks that cover the more important cases. A list of these handbooks published by the National Bureau of Standards appears at the end of this chapter. Where unusually high voltages are used, or other exceptional features are present in a generating installation, safety can be assured only by careful measurements by specialists of exposure at stations occupied by personnel under actual operating conditions. Lead thicknesses given by Kaye[7] for x-ray voltages up to 5 Mev. are included in Table 6.

8. Unnecessary Hazards

Under this title should be considered those uses or misuses of x-radiation that serve no real purpose and unnecessarily expose individuals to possible injury. It is needless to say that all such procedures should be discouraged. Two examples may be cited to illustrate. In some shoe stores, x-ray machines, under no expert supervision, are occasionally used to permit customers to examine the bones of their feet by means of a fluoroscope after fitting new shoes. Since no limit is set on the duration of such exposures, it is surprising that numerous cases of injury have not come to light. Another illustration occurred during World War

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[7] G. W. C. Kaye, *Nature*, **145**, 370 (1940).

II in a large industrial plant where employees were permitted to use a medical x-ray installation to examine themselves for metal splinters, or make any other use of the machine that struck their fancy. This occasioned an outbreak of severe radiation dermatitis, and possibly other injuries that were not immediately identified by examining physicians. Considerable damage was done before a correct diagnosis led to the cause and the practice of self-examination was discontinued. The obvious conclusion from all such incidents is that no x-ray machine should be operated by other than a trained technician well aware of the limits of safe exposure and of the consequences of overexposure. Furthermore, the technician should be responsible for the enforcement of adequately safe procedures in all operations involving the use of x-ray equipment. In no other way can a certain degree of carelessness, either through ignorance or foolhardiness, be prevented.

III. Infrared Radiation

A. GENERAL EFFECT

The long wave lengths of infrared (heat) radiation can inflict no deep injuries in the human body, since they are readily absorbed by the surface tissues. Although the full effects on the surface tissues do not develop for several hours, there is almost immediately some discomfort associated with overexposure to this type of radiation. This discomfort gives adequate warning as far as general bodily injury is concerned. The eyes, however, may suffer from continual exposures to infrared radiation that is well below the level that causes general discomfort or injury. There is some evidence that this may result in a cataract.[8] Dunn,[9] however, found no cataract from infrared in the glass industry.

Although only a small portion of the energy is absorbed in the lens of the eye, the lens cannot lose heat readily. An additional injury is a permanent necrosis of the retina, most likely to occur in unprotected eyes exposed over long periods at some distance from the source of radiation. Fortunately, in most situations where overexposure of eyes to infrared radiation may occur, visible radiation also is so intense as to require protective goggles. This may not always be true. Where sources of infrared are encountered in routine operations at such a low temperature that little visible light is emitted, special attention must be given to the protection of the eyes.

B. PROTECTIVE MEASURES

The effects of excessive heat on bodily comfort and resistance can be reduced somewhat by taking salt tablets and drinking plenty of water to replace evaporational losses due to perspiration (see page 119).

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[8] G. F. Kealing, J. Pearson, J. Simons, and E. E. White, *A.M.A. Arch. Ind. Health,* **11,** 305 (1955).

[9] K. L. Dunn, *Arch. Ind. Hyg. and Occupational Med.,* **1,** 166 (1950).

Absorbent radiation screens are effective if not placed too close to the individuals protected. Since they absorb this radiation readily, they rise in temperature and, if not cooled, will re-emit part of the energy received. Reflective screens of polished aluminum sheet are very effective in many industrial situations. They are used to direct the rays away from personnel into unoccupied space or, better, return them to the furnace or other heat source (see Chapter XXI).

Eyes should be protected, by suitable glasses, from direct radiation arising from areas that give off intense heat, even though the temperature is not necessarily high.

IV. Corpuscular Radiation

Under this heading may be grouped alpha particles, beta particles, protons, and neutrons. Alpha particles have very low penetrating power so that sources of this type of radiation external to the body can produce very little biological effect at intensities usually encountered. They are stopped completely by a few inches of air. They do represent a serious source of injury when the substance emitting them is inside the body, a subject discussed in Section V.

A. BETA RAYS

The beta rays from radium, and from many of the artificially radioactive isotopes, have a much greater penetrating power than do alpha particles, at very high energies being able to traverse a considerable fraction of an inch of animal tissue. Therefore, when strong sources are handled that emit only beta particles, screening must be used. Fortunately, approximately one eighth of an inch of lead, iron, or brass will absorb most radiation of this type completely. An equivalent amount of glass in weight per square inch is likewise effective. Overexposure to beta rays will produce effects in the skin and adjacent tissue. Serious burns can result from this type of overexposure, particularly on the hands. Many radioactive isotopes that emit beta particles also emit gamma rays, and the precautions for protection from the penetrating radiation will insure safety from beta particles also.

B. NEUTRONS

1. Types and Effects

The development of sources of nuclear energy for industrial applications gives considerable importance to the problem of protecting industrial employees from neutron radiation, a subject previously of interest only to a relatively small number of individuals engaged in research in this field.

The neutron is a particle of approximately the mass of a hydrogen nucleus but without electric charge. Therefore it does not ionize atoms directly to any important extent. However, secondary products of its reaction with matter are charged particles that do produce ionization and are, therefore, biologically dangerous. There are a variety of ways in which these secondary effects are produced, but for practical purposes we may divide neutron radiation into two general classes characterized by the speed with which the neutrons are moving. Those moving at average speeds near the speed of the thermal agitation of molecules at ordinary temperatures are classed as slow or thermal neutrons. Those moving at definitely higher speeds are classed as fast neutrons, and may have energies up to several million electron volts, whereas the thermal neutrons have energies of about 0.03 electron volt.

The effects of these two classes of neutron radiation are quite different in relation to biological hazards. When tissue is irradiated by fast neutrons, the biological effects are produced by protons ejected from hydrogenous material as a result of a more or less direct collision. The effects will depend on the energy of the neutron beam as well as on its intensity and, since fast neutrons are not readily absorbed by matter, these effects will occur all through the tissue.

Thermal neutrons, on the other hand, are absorbed in most substances, especially boron and cadmium. When incident on the body they are absorbed into the nuclei of atoms in the tissues and give rise to a nuclear reaction in which gamma radiation is released. Also, the capturing nucleus may become radioactive. Thus, irradiation by thermal neutrons produces sources of ionizing radiation within the body. Because these effects are not readily studied in detail, and it is difficult to estimate the actual dosage of the radiation generated, it has been considered desirable to reduce neutron exposures as far as practicable.

2. Tolerance

The question of tolerance for neutron dosage has not yet been answered completely. The most common solution is to estimate the energy delivered to the tissue by measuring it through removal from the beam of neutrons, and introduce a safety factor reducing the tolerance level, based on the principle of the roentgen, to take care of increased biological effects that may result from reactions released by neutrons within the body. This argument applies particularly to fast neutrons, which may be measured by an ionization chamber having hydrogen atoms in its walls. The commonly accepted safety factor for reducing the tolerance level has been 10, represented by the relative biological effectiveness of 10 given in Table 1.

The tolerance level for thermal neutrons is an even more debatable quantity. The relative biological effectiveness has been generally assumed to be about 5. This factor will depend considerably on how the intensity of the thermal neutrons is measured. Fortunately, under practical conditions some of the effects of thermal neutrons will be measured as beta or gamma radiation by personnel meters and, therefore, exposures to thermal neutrons will be detected even if not identified. If these exposures approach tolerance levels a survey of working conditions often may reveal the source.

In fact, where slow and fast neutrons are encountered, in practice, potential gamma ray exposure will also be present, therefore, it is important to control exposures in terms of all three radiations. Thus, if the ordinary gamma ray type of pocket ionization chamber is designed to measure fast neutrons it will be sufficient whenever the total reading gives a value well below tolerance level. In some installations, where alterations of equipment or procedures are infrequent, this condition can be ascertained by survey measurements, which can be made more accurately than by pocket meters. In some cases monitoring instruments located at strategic points and operated continuously during working hours may be desirable. Such monitoring arrangements may be a necessity where a variety of different operations are performed or where accidental increases in the level of the radiation may be anticipated.

3. Shielding

Shields for the two types of neutrons, swift and slow, are as different as their properties would indicate. Since fast neutrons are reduced in energy and finally stopped only by more or less direct collisions with atomic nuclei, most effectively with hydrogen nuclei, a shield for fast neutrons should contain plenty of hydrogen. Water and paraffin are good examples. When these neutrons have been reduced to thermal velocities their properties are the same as those of any other thermal neutrons.

Boron and cadmium are quite opaque to thermal neutrons so that thicknesses of these metals of the order of 0.040 inch will screen them off completely. In the case of cadmium, gamma rays are generated by the capture of neutrons, and whenever high intensities are involved, a layer of lead or other dense material must be placed between the cadmium layer and personnel to be protected. The adequacy of this layer should be checked by measurement of the radiation.

V. Poisoning from Radioisotopes

The discussion of radioactive poisoning will be based on the facts developed in connection with the poisoning of radium dial painters in this country following World War I. The principles involved apply to any other radioisotopes that are concentrated in the bone structure, such as radioactive strontium or calcium. However, the presence of these artificially radioactive substances is not as easy to detect and measure because with radium the radon gas can be used as a radioactive tracer. Therefore, greater precautions are required to ensure that the environmental conditions of the employees preclude the possibility of ingestion or inhalation of potentially dangerous amounts.

A. RADIUM POISONING

1. Historical Summary

Radium poisoning as a definite source of injury was first brought to light in this country through a report, in 1924, by Blum, a New York dentist, who encountered a case of chronic osteomyelitis in the mandible of a girl engaged in applying radioactive paint to instrument and clock dials. Without any knowledge of the kind of material with which this girl worked, he concluded that the nature of the affliction was so unusual that it must result from some type of occupational poisoning, and published a statement to this effect.[10]

In the following year, Hoffman,[11] who was asked to investigate the plant in New Jersey where the girls were employed to apply radioactive paint, found from an examination of death certificates of deceased former employees that these certificates were strikingly similar, although made out by different family physicians, who were entirely ignorant of the true cause of death. There was frequent mention of jaw necrosis, anemia, and buccal lesions, although the immediate cause of death was usually given as some well-known disease that exhibits some of these symptoms. It was highly improbable, in Hoffman's opinion, that this could be accidental. After he had assembled data on five deaths and twelve living cases, where infected jaws and anemia were predominant features, he concluded that they represented a new type of occupational poisoning, since all cases had worked at the same plant. From his investigations of the working conditions and the nature of the material applied by these employees, he also formed the opinion that the mesothorium in the paint had something to do with the symptoms observed. This opinion was further confirmed in his mind by the observation that after dipping their brushes in the radioactive paint the girls habitually pointed them between their lips. This practice would give an excellent opportunity for ingestion of the paint.

These preliminary reports led to a series of investigations, sometimes with contradictory conclusions. In many cases the radioactive constituent of the paint was ignored and some other source of the disease was sought. However, in the same year Martland[12] examined two girls who were suffering from extensive jaw necrosis and anemia. Both girls died and, as a result of autopsies that he performed and of investigations on living patients suffering from the same symptoms and engaged in the same work, he was able to formulate an extensive report which clearly, for the first time, traced the disease to its true origin.[13] From an examination of the expired air, he was able to detect the presence of radon by the large number of alpha particles revealed by a zinc sulfide screen in a darkened room when the subject breathed against it. From the skeletons, after death, he proved the presence of radioactive material in the bones by electroscopic and autoradiographic tests. By chemical extraction methods he recovered 150 micrograms of radium from one skeleton. At the same time, from examinations of patients suffering with the disease, he was able to describe more accurately the type of anemia, as well as the nature and progress of the bone lesions. In this

[10] T. Blum, *J. Am. Dental Assoc.* (1924).

[11] F. E. Hoffman, *J. Am. Med. Assoc.*, **85**, 961 (1925).

[12] H. S. Martland, P. Conlon, and J. P. Knef, *J. Am. Med. Assoc.*, **85**, 1769 (1925).

[13] H. S. Martland, *J. Am. Med. Assoc.*, **92**, 466, 552 (1929).

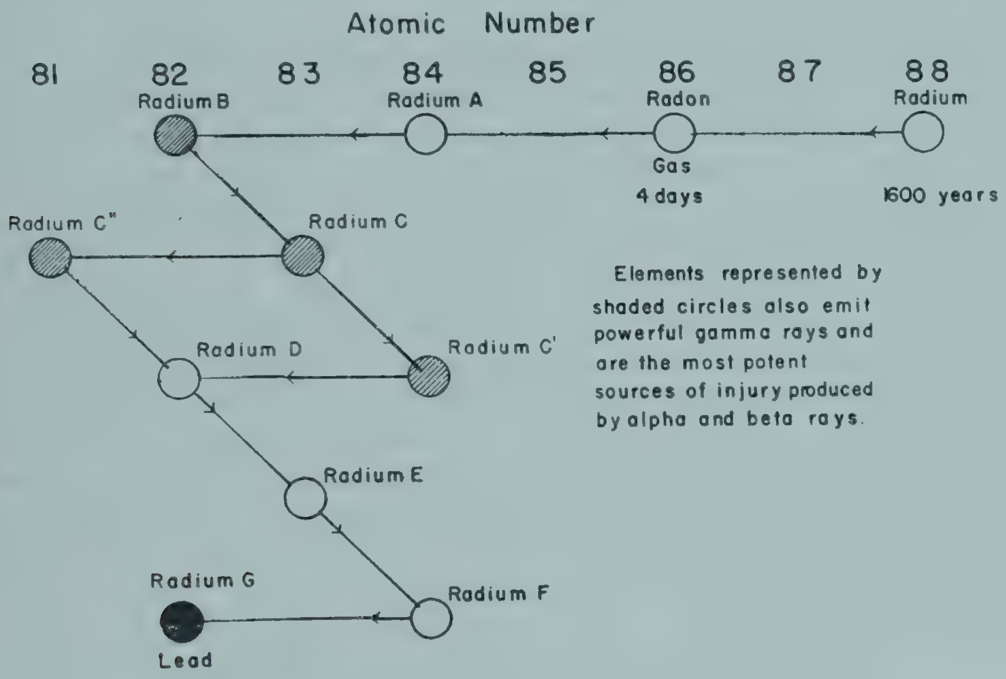
way, he accumulated information that would provide easy identification of the disease from its symptoms. As a result of this clarification of the picture, it became evident that deaths of workers at least as early as 1922 had been the result of radium poisoning, although attributed by family physicians to other diseases. It is estimated that eventually at least 40 persons died from this disease.

It is of interest to consider the general environment under which these tragic circumstances developed. In the period of World War I and immediately thereafter, about 800 girls, at one time or another, were employed in one plant in New Jersey as radium dial painters. There were other smaller plants in and around New York City. The considerable demand for radium dials for military use caused this rapid expansion of a very small industry, and employees were recruited from other types of work where similar skills were required. Usually, they were paid in accordance with the number of articles completed per day, and were not warned of any particular hazard, since the dangers from the ingestion of radium were not then understood. Consequently, they adopted procedures that would enable them to produce acceptable work at the most rapid rate. Many of these people had applied other types of paint, in previous employment, which were not sufficiently toxic to produce any ill effects if the fine brushes were pointed by means of the lips. They soon discovered that this was a very effective procedure in radium dial painting. Since the paint consisted chiefly of zinc sulfide suspended in a water solution of gum arabic, occasionally thinned with water to give proper consistency, there was no natural deterrent to the procedure. The amount of radium that a dial painter might ingest under these circumstances has been estimated at from 15 to 200 micrograms per week. This explains in a few words how the situation developed. Early in the investigation, the employers sensed that radium poisoning might be the cause of the deaths and injuries, which were rapidly mounting, and ordered the practice of tipping brushes with the lips discontinued. However, such a regulation was difficult to enforce, and it was not until the advent of plastic adhesives with organic solvents of disagreeable taste and odor that the practice was entirely eliminated.

Although it has been well established that the practice of pointing the brushes with the lips was the predominant cause of the injuries, there are alive today, in apparent good health, workers who used this method for a number of years. This fact is mentioned to show that part of the confusion in arriving at a solution of the problem arose from individual differences among the employees. Those who survived apparently developed a method of pointing the brushes that did not result in ingestion of appreciable amounts of paint; others were more careless in this respect.

2. Radioactive Nature of Radium

Radium is always accompanied by its decay products in amounts dependent on a number of conditions associated with the previous chemical history of the preparation. The properties of a sample of radium in equilibrium with its decay products will be more readily understood by reference to Figure 3, which shows the genetic relationships in the radium family. We see that the immediate product of radium is a gas, radon, which decays to half-value every 4 days after removal from the source of supply, radium. This transformation is accompanied by the emission of an alpha particle for each atom transformed. By emission of another alpha particle, radon becomes RaA, which in the same way transforms into RaB. RaB changes to RaC by emitting a beta particle. Here, a branching occurs that reunites in RaD, which by emitting a beta particle becomes RaE, and this substance in the same way transforms into RaF (polonium). By emitting an alpha particle, RaF becomes RaG, an inactive isotope of lead. The cross-hatched circles represent elements that emit the more powerful gamma rays associated with radium. Thus we can see that radon, even after removal from radium, will have associated with it the products emitting the more powerful radiations capable of producing injury. The quantitative relation between the radon generated in a given time and the amount of the parent radium can be used to measure the amount of radium present by measuring the rate of production of radon.


Atomic Number
81
82
83
84
85
86
87
88
Radium B
Radium A
Radon
Radium
Gas
4 days
1600 years
Radium C"
Radium C
Elements represented by shaded circles also emit powerful gamma rays and are the most potent sources of injury produced by alpha and beta rays.
Radium D
Radium C'
Radium E
Radium G
Radium F
Lead

The Radium Family

Figure 3. The genetic relation of various products originating from the transformation of radium. Heavy black arrows pointed horizontally to the left represent the emission of alpha rays. Diagonal arrows to the right represent the emission of beta rays. Cross-hatched circles represent members that emit strong penetrating gamma rays.

Radium Luminous Compound. Radioactive luminous compound, as ordinarily used in radium dial painting, consists of a mixture of phosphorescent zinc sulfide and radium. In some instances mesothorium, a radioactive isotope of radium, was used in place of radium, but for economic reasons the use of mesothorium has been discontinued, so we may confine our discussion to the compound containing radium. It should be noted in passing that the effects of mesothorium are very similar to those of radium, but the methods of detection and measurement are somewhat different.

Since World War II large quantities of artificial radioisotopes have become available, some of which emit only a strong beta radiation. The absence of the penetrating gamma radiation, always present from a preparation of radium, makes such radioisotopes attractive as an ingredient of a self-luminous paint. The only drawback is that most phosphorescent compounds are only slightly activated by beta particles in comparison with alpha particles from radium. This disadvantage has been overcome to a considerable extent by using larger amounts of the beta ray–emitting radioisotope, chiefly Sr^{90}, and by developing phosphors more sensitive to beta particles. Although, fortunately, no case histories of deaths from Sr^{90} are available, it can be predicted that ingestion of this radioisotope would produce injuries quite similar to those produced by radium and that might be indistinguishable for equal dosage of radiation energy. Therefore, the same caution must be used in handling such radioactive paints as for radium paints. As has been mentioned, it is more difficult to measure this artificial radioisotope in the living human body since it neither produces a gaseous decay product nor emits gamma rays. Therefore, it is almost impossible to detect this kind of poisoning in its incipiency, a procedure now readily possible with radium poisoning.

3. *Injuries and Symptoms of Radium Poisoning*

The study of the early severe cases of radium poisoning revealed quite definitely that they involved a radiation injury that, although differing in some respects from other known types, was produced basically in the same way. The chief difference from the kinds of exposure already mentioned in this chapter lies in the manner in which the dose of radiation was administered to the cell structures, and in the chief ionizing agent responsible for the injury. It is now well established that the alpha rays from radium and its decay products, deposited in the bone, produced most of the observed injury to bone structure and to the blood-producing centers in the bone marrow. Although alpha rays can penetrate only a very thin layer of tissues, they produce a dense column of ions that probably affect most of the cells in their path. With the sources of the alpha rays distributed through the bone tissue itself, it is easy to see how great damage could, and did, result. This situation was aggravated by the further well-established fact that radium, once deposited in the bones, is eliminated very slowly, and no satisfactory therapeutic means for speeding up this elimination have been found.

Some of the more severe effects and symptoms of radium poisoning have been mentioned in the discussion of the history of this hazard. These symptoms are not to be regarded as helpful in future control of radium poisoning, since it is now known that almost all detectable symptoms appear only in late stages of the disease. This is revealed by the apparently contradictory indications encountered in many early cases studied. We need recall only a few, such as the development of osteogenic sarcomas, which usually proved fatal a few months after they were discovered, while at the same time the blood picture remained practically normal. This shows clearly that the blood count cannot be relied upon to guard against the effects of radium poisoning. On the other hand, anemias that refused to yield to treatment and eventually proved fatal were found in some radium dial painters. The study of the deviations from normal in the blood counts in these cases contributed to the solution of the real cause of the disease but, even here, offered no protection to the victim. Therefore, it is obvious that physiological symptoms and indicators may, and usually do, appear too late in the progress of the disease to be of any value as a safeguard. When they do appear, they show that the injury has reached a dangerous stage, where the outcome is at best doubtful. We may conclude that periodic medical examinations of employees in this industry are of value in determining whether they are otherwise in good health, but have little bearing on prevention of radium poisoning. Regular blood counts have a similar significance, and also may serve to detect cases of radium poisoning that have occurred in spite of protective measures. However, to produce such cases the violations of rules of proper procedure must be so flagrant and habitual that they ordinarily should be detected by measurement of radon in the exhaled breath, if not by direct observation, long before a stage of serious injury could result. The physical measurement of the amount of radium in a living body is now so easy at levels that begin to be hazardous that routine measurements cannot fail to reveal the beginning of the accumulations of radium in the body before it becomes dangerous.

4. Tolerances

Before discussing methods of detecting the presence of radium in the living body and the quantitative estimation of the amount by measuring the radon in the exhaled breath, we shall discuss the levels at which it is desirable to hold this quantity, as well as the amount of radon permissible in the workroom air, to prevent injurious effects.

Expired Air. Although we do not have all the information we would like regarding the amount of deposited radium that can be tolerated by a living person, nor even regarding the amount of radium that a normal healthy person, never exposed to concentrated sources of radium, may naturally carry in his body, it is fairly well established that as little as 2 micrograms may prove fatal. By available methods to be discussed, the equivalent of 0.1 microgram can be detected reliably. Proceeding on the now generally admitted principle that any radium deposited in addition to natural amounts is too much, we can say that as soon as the fixed or habitually carried radium becomes reliably detectable the limit has been reached, and the employee so affected should be removed from any possibility of increasing this amount of radium. This quantity of radium will produce a radon concentration in the expired air of approximately 10^{-12} curie per liter. Therefore, when measurements reveal a concentration of radon in excess of 10^{-12} curie per liter, this can be accepted as evidence that additional radium is deposited in the body.

In interpreting the significance of the measurement of radon in the expired air, the occupational record of the subject from whom the sample was taken must be considered. The term "fixed" radium has been used to denote the radium that is in a slow process of elimination from the body. In the period immediately following ingestion, the radium is eliminated rapidly—approximately 70 per cent in the first 24 hours and about 95 per cent in five days. After this, the elimination is very slow. Therefore, if a sample of expired air is taken on a day subsequent to a period of several days of continuous dial painting, part of the radium indicated by the measurement of radon may be eliminated in the next few days and, if no further exposure occurs, in a subsequent measurement a few days later there will be a noticeable decrease in the radon content of the expired air. This decrease is enhanced by the fact that some of the radium indicated by the first measurement was probably not yet deposited in the bone. A larger amount of radon would appear in the lungs from this radium than from radium more or less permanently deposited in the skeleton. Circumstances of this kind have an important bearing on the recovery of an individual whose breath has an abnormal radon content. They also make it evident that detailed occupational records of dial painters should be kept as an aid in interpreting the results obtained from measurements of radon in the breath.

Workroom Air. There is definite evidence that radon, when inhaled, can produce injuries such as leucopenia, and possibly lung cancer. When the concentration in the atmosphere reaches 10^{-7} curie per liter, anemias can be expected to become clearly evident, the severity depending on the period of exposure. It is also known that when this concentration is reduced to the order of 10^{-9} curie per liter, individuals suffering from leucopenia will recover.[14] Therefore, tolerances for workroom air have been variously set at 10^{-10} to 10^{-11} curie per liter. In most dial-painting plants, the lower limit is readily attainable by adequate ventilation in conjunction with other usual protective measures. In view of the fact that even the higher concentration is, so far as is definitely known at present, presumably safe, it seems a matter of judgment as to which limit should be enforced.

[14] J. Read and J. C. Mottram, *Brit. J. Radiol.*, **12**, 54 (1939).

5. Detection of Unsafe Conditions

Radiation as an Indicator. With the failure of physiological symptoms as a guide in detecting incipient exposure to radium poisoning, the question arises as to what means are available to reveal, early enough to forestall damage, conditions that may ultimately result in injury if uncorrected. Inasmuch as radium and radon are the sources of radiation that produce the injury, it is natural to look for some method that will detect their presence at points where injury may be produced. Fortunately, the powerful ionizing effects that produce biological changes also offer a ready means for revealing the presence of radon and radium quantitatively. It is necessary to establish some order of tolerance on the amount of radioactive material that may be present, to set up procedures for detecting unsafe conditions long before any real damage has been inflicted. Although such procedures may not in all ways represent the ideal, they are far in advance of any other now available, and it has been amply demonstrated that, if followed correctly in all details, they will prevent not only detectable injury but also all but very minor damage. In using radiations from radioactive elements in detecting unsafe conditions, certain precautions must be taken to ensure that the radiation measured arises from locations where it may cause injury. For this reason, methods of detecting radium in living persons that depend on measurements of gamma radiation, such as with ionization chambers and Geiger-Müller counters, are open to the objection that sources of gamma radiation external to the body may contribute to the measurement. If the subject under investigation happens to have radioactive material on the skin, or in the hair, this material also will be measured and thus lead to a false result. This difficulty is encountered to an even greater extent in any attempt to test the air of workrooms by gamma-ray methods. Therefore, measurement of the radon in samples of air of definite origin by means of the alpha radiation will lead to more reliable results from the standpoint of interpretation. Where desirable, these measurements can be evaluated in terms of the amount of radium that produced the radon.

Although a chapter on the measurement of nuclear radiation appears in Volume III of this book where the more general types of instruments are discussed, the equipment and methods for measuring low concentrations of radon are specialized and relate so directly to the problem under discussion that a description is given here.

Methods of Radon Measurement: Sampling methods, flasks. In the early investigations, measurements of radon concentrations were made with portable ionization chambers connected to gold-leaf electroscopes. With considerable care, such equipment will yield satisfactory results and it sufficed for these studies because the concentrations of radon in the breath of persons about to die of radium poisoning were several hundred times that in the breath of an individual who is just beginning to accumulate more than an average normal amount of radium in the body. For the determination of the order of 10^{-13} curie of radon, required for detection of slight increases in the normal radon content of expired air, such methods are not generally reliable. Therefore, the measurements must be made in specially equipped laboratories by experienced technicians along the lines now to be described. This requires that the samples of expired air be sent to the laboratories in suitable flasks. The half-life of the radon is sufficient to permit its shipment by air to any point in the United States for measurement if there is no delay in handling. The activity decreases 18 per cent per 24-hour day and even two days after sampling a significant fraction of the original activity remains. Measurement in a central laboratory has the additional advantage that all observations are more likely to be directly comparable than those made locally or in several laboratories under slightly different conditions. However, radon standards, in the form of dilute solutions containing known amounts of radium, are available from the National Bureau of Standards so there is no real excuse for marked variations in measurements made at several laboratories if apparatus of comparable sensitivity and reliability is used.

Laboratory measurements of samples of air containing radon are based on a comparison between the radon in the sample and a standard quantity of radon of similar magnitude. The standard quantity of radon is obtained from a standard solution of radium carefully prepared for this purpose. From the known rate of accumulation of radon in such a solution, various quantities of radon can be obtained up to the equilibrium amount, by allowing the radon to accumulate over various periods of time. The growth of radon is given by the relation $R = E(1 - e^{-0.18t})$, where R is the amount of radon at any time t, measured in days since its removal from the radium source; e is the base of natural logarithms; and E is the equilibrium amount, equal in curies to the number of grams of radium in the standard solution. About 30 days are required to reach practically the equilibrium amount since after this time $e^{-0.18t}$ is for practical purposes equal to zero. One half the equilibrium amount is obtained in 3.83 days so that various fractions of this amount may readily be obtained down to those so small that the accumulation time is difficult to measure accurately.

The comparisons may be made by several methods, but in each the ionization produced in an ionization chamber, by the alpha particles, is the effect customarily used. The number of alpha particles produced per hour, or other convenient unit of time, is proportional to the quantity of radon in the chamber. This number may be determined by direct counting of the current pulses in the ion chamber produced by the alpha particles, or by measuring with a sensitive electrometer the current produced by the alpha particles traversing the gas in the chamber at any time, which is indirectly a method of determining the number of alpha particles emitted per unit of time.

In addition to being dependent on the properties of the equipment used, the accuracy of all such measurements is dependent on statistical laws governing the evaluation of random events, since alpha particles are emitted by any radioactive source at a purely random rate. When this rate is low, as for the smaller quantities of radon, these fluctuations become obvious. This means that a sufficient number of particles must contribute to the measurement to reduce the standard deviation to the required percentage of the total number observed. Since in this case the standard deviation is equal to $\pm\sqrt{N}$, where N is the total number of particles recorded, an observation including 100 particles has a standard deviation, on a statistical basis alone, of ±10 or ±10%. To achieve a statistical accuracy of ±1% it is necessary to record 10,000 particles. Whether this condition is properly fulfilled is most conveniently determined in a method in which the alpha particles are counted directly. The counting method offers other advantages that make it more convenient to use. If, to secure the desired statistical accuracy, the time of observation must be extended over a significant fraction of the half-life of radon, correction must be made for the decay of the radon in the chamber. Furthermore, because some of the immediate decay products of radon emit alpha particles and contribute to the measurements, observations can be begun only after these have come into transient equilibrium with the radon after its introduction into the ion chamber. This period is of the order of three hours.

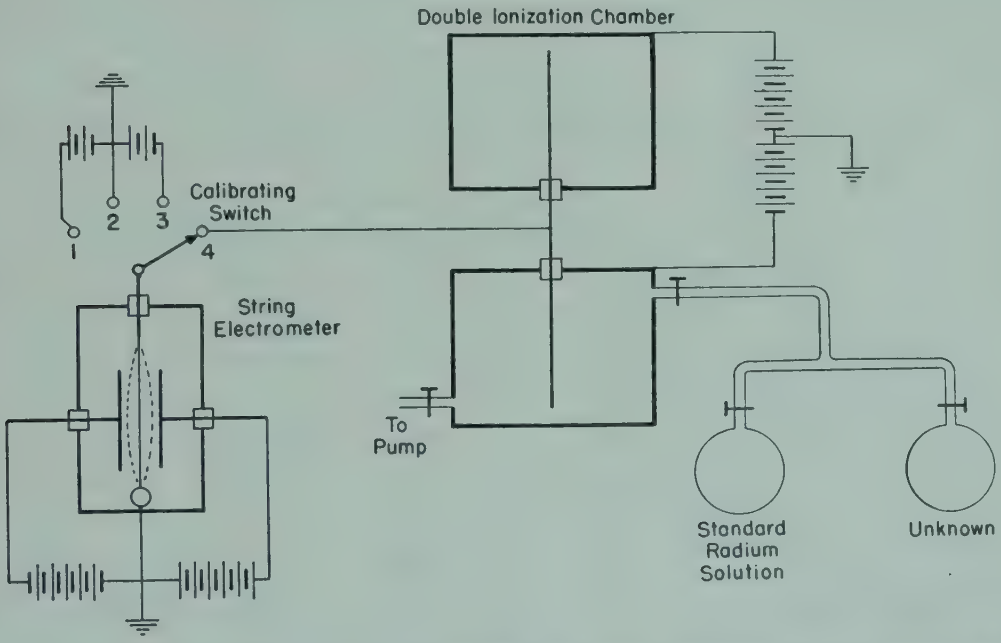


Figure 4. Schematic diagram of the essential elements of equipment for measuring samples of radon by the use of a string electrometer to measure the ionization current produced by the alpha rays from radon in an ionization chamber.

A schematic diagram showing the method[15,16] of using an electrometer for comparing radon samples is shown in Figure 4. A double ionization chamber, with the collecting voltages of the two chambers opposed, is used, as shown, to neutralize the effects of external sources of radiation. The radon is introduced

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[15] W. D. Urry and C. S. Piggot, *Am. J. Sci.*, **239**, 633 (1941).

[16] R. D. Evans, *Rev. Sci. Instr.*, **6**, 99 (1935).

into one of the chambers, as indicated. To make the recording of this equipment automatic, the calibrating switch is actuated by a synchronous motor so that the arm contacts points 1, 2, 3, and 4 in succession once each hour, and the position of the fiber of the electrometer is recorded by a special camera using a slowly moving sensitized paper. The switch impresses a positive and an equal negative voltage on the fiber, and finally connects it in a charged position to the ion-collecting system of the ionization chambers, where it remains during the subsequent hour to record the loss of potential due to the net ionization current produced by the radon in the lower chamber. Provision is made to introduce into the radon chamber either a standard quantity of radon for calibration, or the unknown sample. This method requires very steady voltages on the knife edges of the electrometer and the ionization chambers, as well as the best quality of insulation for the electrometer fiber and the ion-collecting system. Because of changes produced in the sensitivity of the system, measurements must be corrected for changes in the electrostatic capacity of the collecting system. The sensitivity must be adjusted for each sample that differs appreciably in amount from the preceding one. A considerable disadvantage is that the photographic film or paper must be processed and the record evaluated before the results can be computed.

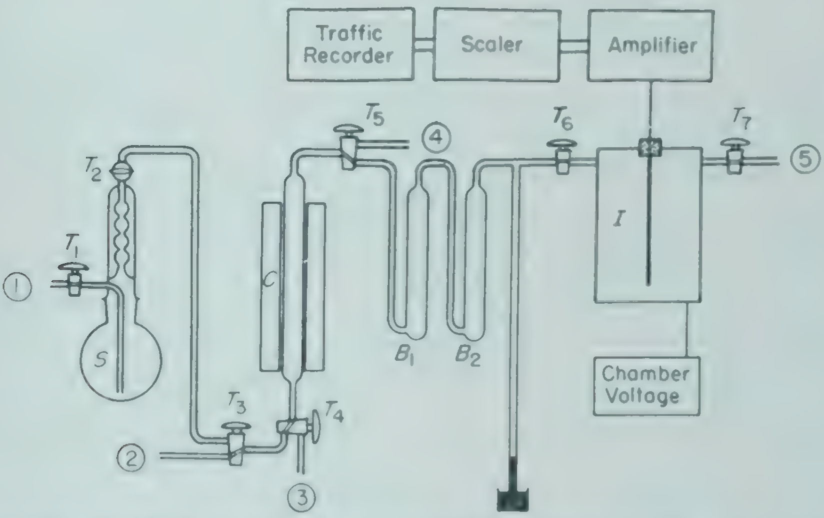

Figure 5. Diagram of purifying system and apparatus to count the alpha particles from a sample of radon in an atmosphere of pure nitrogen.

A similar schematic diagram is shown in Figure 5 for comparing small quantities of radon by counting the alpha particles.[17] Since the individual particles are enumerated and external sources cannot, in general, produce current pulses similar to those that result from the passage of an alpha particle through the gas, only one chamber is required for this method, which, among other things

[17] L. F. Curtiss and F. J. Davis, *J. Research Natl. Bur. Standards*, **31**, 181 (1943)

reduces the background of the measurements by 50 per cent. This chamber is shown at *I* in the figure. It consists simply of a cylinder of about 4 liters capacity with a central insulated electrode extending along the axis. When a voltage is applied to the cylinder, the collecting rod experiences a sudden rise in potential as the ions generated by each alpha particle are collected on it. To make this voltage pulse sufficiently short in duration for proper amplifications and counting, pure nitrogen must be used in the ion-counting chamber. In some cases a small addition of CO_2 also may improve the performance. To provide an atmosphere of pure nitrogen in the chamber, the radon sample, whether from the standard radium solution, *S*, or an unknown from an expired air sample, is passed through the tube, *C*, containing reduced copper heated in a furnace to approximately 500° C. Moisture is removed by the drying bulbs, B_1 and B_2, after which the sample, consisting now of pure dry nitrogen plus radon, passes into the evacuated chamber, *I*. Sufficient nitrogen is then added through the system to make the pressure in the chamber equal to that of the atmosphere. A sample of air containing radon can be prepared similarly by attaching the flask at (*2*) or (*3*) and flushing it by a stream of nitrogen through the system into the chamber.

To count and record the alpha particles, the voltage pulse produced by each particle is amplified by a conventional electronic pulse amplifier sufficiently to operate a scaling circuit which transmits every eighth pulse to the counting mechanism of a commercial recorder designed originally for counting vehicles passing along a thoroughfare, by means of photo cells. These machines print, on a moving strip of adding machine paper, the total accumulated count with the hour of the day and the day of the week. This record is immediately available at the end of the period of observation and can be evaluated by a few simple calculations. The advantages of this counting method are: (*1*) no photographic process is involved; (*2*) moderate quality of electrical insulation is sufficient for the collecting electrode of the ion chamber; (*3*) no adjustment of the ion chamber constants is required for various sizes of samples over a wide range; (*4*) the potentials used need not be accurately known, nor accurately constant from day to day; (*5*) the number of events contributing to the measurement is immediately available for evaluating the statistical accuracy of the measurements. Although a considerable amount of electrical and electronic equipment is needed, it is all used in circuits that are readily serviced and require little care beyond the replacement of electronic tubes as they become worn out.

A convenient form of flask for taking samples of air containing radon is shown in Figure 6. It is made of Pyrex glass with a central tube, projecting from the special stopcock to near the bottom of the flask, through which nitrogen is passed to flush the sample into the measuring chamber. A glass stud, fitting loosely inside this tube, projects from the bottom of the center of the flask to avoid breakage of the tube due to vibration during shipment. The flasks are mounted in heavy metal cans with supports for holding the flasks similar to those used for vacuum bottles for hot liquids. Flasks may be used to take samples of workroom air, or of expired breath. They may be sent out evacuated so that a sample of workroom air can be obtained merely by opening the stopcock a the place where the sampling is desired. It is well to evacuate the flasks several days before shipment and test the vacuum every 24 hours with a high frequency coil that produces an electrodeless discharge inside the flask. This permits the elimination of flasks with imperfectly fitting or poorly lubricated stopcocks. To take expired air samples the exhalation is accumulated in some type of gas bag (a basketball bladder is adequate), which is then attached to the tubulation of the stopcock and the stopcock opened.

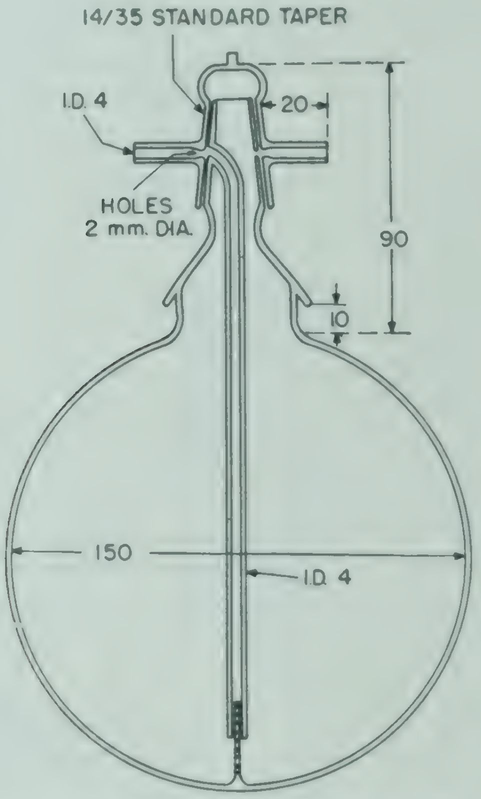

Figure 6. Cross section of a Pyrex glass flask suitable for taking samples of room air or of breath of workers in radium dial plants for determination of radon content. All dimensions are in millimeters.

In using such flasks, a few simple precautions must be observed. An expired breath sample should be taken only after the worker has been out of the plant at least 4 hours, preferably before entering the plant in the morning. Direct experiments show that the air in the lungs has lost most of the radon acquired from the workroom air in from 3 to 4 hours. This procedure insures that only radium in the body contributes radon to the sample. Various suggestions have been made regarding the breathing methods that give most satisfactory samples. It should be arranged that alveolar air is taken in the sample as far as practicable. Also it is very important that the sample be taken where the atmosphere contains no radon contamination, preferably in the open. Otherwise, the subject should be in the room where the breath sample is taken about an hour before the sampling is made, and a sample of room air should be taken as a control. In taking air samples in workrooms, it is important to exclude any possible radium-bearing dust from the flask. Since most workroom air contains such dust, a simple filter is recommended.

6. Protective Rules for Radium-Dial Painting

The following suggested rules for protection of workers handling radium luminous compound will, in general, apply to the handling of any similar radioactive material that can be ingested or inhaled. These rules are intended to cover routine work with radioactive substances. Many of the suggestions are taken from regulations in Handbook H27 of the National Bureau of Standards, *Safe Handling of Radioactive Luminous Compound.* Fundamentally, protective rules should aim at the prevention of ingestion or inhalation of radioactive substances during the necessary manipulations. All evidence available at present indicates that this precaution will eliminate all serious injuries that might be caused by the radioactive constituent of any radioactive luminous compound. If this principle is successfully followed, it should prevent all minor damages that might result from this type of work. To secure this result, a generally safe and clean environment must be provided for the employee, and his full co-operation must be enlisted in the observance of a few rules, none difficult to follow, which impose but slight restrictions on the quality and the quantity of the work he can accomplish.

Gamma-Ray Hazards. Since the quantity of radium in radium luminous compounds is small, and since Sr^{90} has no gamma rays, it is only in large plants, employing more than 25 people and using the radium compound, that there is likelihood of overexposure to gamma radiations. In all situations where such exposures may be excessive, the precautions discussed in a preceding section dealing with penetrating radiation should be followed.

Selection of Personnel. It is obvious that the problem of safeguarding the health of a dial painter is greatly simplified if only normally healthy individuals are employed. There were strong indications that some of the early radium poisoning cases were greatly aggravated by complications developing from other maladies simultaneously present. This situation arose because no physical or medical examinations, other than those used routinely for all employees, were then required of persons entering this work. Moreover, persons with certain types of afflictions and diseases may be more susceptible than others to the hazards of this industry. It is also important to make certain that the applicant is not already suffering from exposure to unsatisfactory conditions in previous employment as a dial painter. This item is not as important as it was formerly because there are now very few, if any, plants where proper procedures are neglected. In the years immediately succeeding the uncovering of the cases of radium poisoning, however, it was not uncommon for applicants transferring from one dial-painting plant to another to deny any previous experience because it might prejudice their chances of securing the new job. Therefore, it is to the best interests of all concerned to require rigid medical examinations, including blood counts, of all prospective workers. In particular, those already suffering from anemia or leucopenia, or showing symptoms of tuberculosis, should be rejected. In addition, the expired air should be tested for radon. If, after repeated and careful measurements this exceeds the tolerance limit of 10^{-12} curie of radon per liter of expired air, the applicant should not be employed in this work.

General Procedures. Emphasis should be placed on cleanliness and neatness on the part of all persons in the factory. This must extend to every stage of the work and to all parts of the building occupied by dial painters. Carelessness in personal habits of neatness, and much less in the handling of radioactive compounds, cannot be condoned. A careless worker exposes fellow employees to risks unnecessarily and jeopardizes his own health as well. Great care should be taken to see that any radioactive substance accidentally spilled, whether on a work table or on the floor, is immediately cleaned up and any waste disposed of in a thoroughly safe manner. Workers should wear coveralls or smocks while in workrooms and should keep these garments, as well as hands and hair, free of radioactive material. No food or refreshments of any kind should be consumed in the workrooms, and smoking there should be prohibited.

Brushes. The most satisfactory method of applying radioactive luminous paint seems to be by the use of a small brush. Since tipping of brushes by the lips led to many of the early fatalities, this procedure must be eliminated entirely by most careful scrutiny. Fortunately, the adhesives currently used require organic solvents of unpleasant odor and taste, thus reducing the tendency to point brushes by the lips. The use of bare fingers for this purpose is dangerous, also. One of the most satisfactory procedures for wiping and pointing brushes entails the use of small squares of cleaning tissue, which are discarded immediately after use, into containers reserved for this purpose.

All such discarded material containing radioactive compounds must be frequently and carefully collected and disposed of in such a way as not to constitute a hazard somewhere else, either inside or outside the plant. Large plants frequently return this waste to the manufacturer of the compound for recovery of the radium.

Supervision. One of the best safeguards that can be provided for the protection of dial painters is a thoroughly experienced supervisor, familiar not only with the manufacturing process but also with the stages at which hazards may develop. In spite of instructions, employees are frequently tempted to devise methods and procedures of their own, which may not be safe. It should be the duty of the supervisor to detect and prevent the continuance of any unsafe practices, as well as to instruct the employees in the hazardous nature of the material with which they work and in approved methods of procedure. Routine inspections of employees for neatness and the presence of radioactive material on clothing or hands should be made by the supervisor. Inspection for luminous compound can best be made in a darkened room provided with an ultraviolet lamp of moderate intensity. Even small particles are instantly detected by their fluorescence. It is sometimes convenient to inspect floors and work tables for scattered luminous material by ultraviolet light, making the inspections at night if the rooms cannot be completely darkened.

Equipment. The utensils and equipment used by each dial painter must be kept neat, and should always be arranged in a definite and orderly manner, convenient for the type of work in progress. No untidiness involving radioactive materials can be tolerated. The number of utensils and tools on each table should be reduced to the minimum required for the work, and no articles extraneous to the work should be permitted on the work tables at any time. This refers to the personal effects of the worker, including purses, clothing, cosmetics, and so forth. It is important that the surfaces of all tables on which radioactive compound is handled be smooth and impervious to the solvents used for the adhesive. Likewise, smooth floors that can be cleaned readily by mopping should be provided. Dry sweeping should be prohibited in work rooms.

Storage and Drying of Completed Work. Painted articles should be removed from the vicinity of the worktables frequently, to prevent any considerable accumulation, which might produce a gamma-ray hazard. If these articles are placed in drying racks, such racks should be enclosed and provided with sufficient mechanical exhaust ventilation, at an exit port, to maintain an air inflow of at least 75 linear feet per minute at all other ports and at all cracks when the cabinet is closed. Cabinets containing 500 or more dials should be located at least three feet distant from the permanent station of any worker. Finished dials may be stored on open shelves, if in a physically separated room supplied with ventilation of not less than 400 cubic feet per minute per thousand dials. Since dials in racks and cabinets may be a source of overexposure to gamma radiation, the gamma-ray intensity in their vicinity should be checked by suitable instruments, and workmen should spend only the minimum required time in or near storage areas.

Ventilation. Any operations that produce radioactive dust, such as grinding or scraping surfaces where radioactive luminous compound has been applied, should be avoided as far as possible. Where such procedures are necessary, the operation should be enclosed and protected by ventilation designed to prohibit the escape of respirable particles.

Where any considerable amount of radium luminous compound is applied, the concentration of radon in the air will soon exceed permissible amounts; therefore, a system of forced ventilation is essential. In present plants this ventilation has been accomplished in two ways, both effective if properly installed and operated. Some use general room ventilation adequate to keep radon concentrations below tolerance. Others rely on individual hoods placed over each worktable and connected to an exhaust system. A combination of the two is also used because the amount of air that can be drawn through the hood is limited by the fact that the adhesives in the paints dry quickly in an air stream and are sometimes difficult to apply. Where hoods are used and additional ventilation also is required, it is essential to provide sufficient make-up air to the room at all times, and it is well to equip each hood with an air flow indicator. Ten changes of air per hour, combined with good housekeeping, have been found to produce satisfactory general ventilation in an average dial-painting room.

Hoods for painting dials should be enclosed on all sides except the face, which should have an entrance opening of about one square foot. The glass top should extend to the front edge of the worktable, and sufficient air should be exhausted to maintain an inward flow of 50 to 60 l.f.m. at the face of the hood. Enclosures for the compounding of radioactive paints, that is, mixing the dry powdered pigment with the radioactive constituent or mixing the compound with the adhesive, should be exhausted at a face velocity of not less than 100 l.f.m. Compounding should be done only by experienced technicians who are aware of the hazards involved in handling relatively large quantities of radioactive substances. All precautions required in the handling of millicuries of radioactivity should be observed.

It is obviously necessary that all ventilation described above should deliver the exhausted air to the outside atmosphere, preferably above the roof of the building. The air should not be recirculated or exhausted in a way in which it can be drawn back into the building, either by natural or by forced ventilation.

It must be pointed out that the real criterion in judging the performance of the ventilation system is the radon concentration in the workroom air at the breathing zone of the workers. Any system that keeps this concentration consistently below tolerance is adequate from the standpoint of injuries from radon. Since dial painting should never be permitted even remotely to resemble a dusty operation, the radon is the chief offender to be controlled.

In rooms where radium luminous compounds are manipulated it is necessary to see that ventilating systems are in operation at least a half hour before the employees start the day's work. This precaution is required to reduce the radon concentration in the air that results from an accumulation in stagnant air during the night. Radioactivity tests of room air samples taken at the start of work should be made occasionally to test the effectiveness of this procedure.

Repainting Dials. Repainting of radium luminous figures on dials must be done with caution. The old compound contains essentially all the radium it had originally, and it must be removed under the same precautions required for any similar radioactive material. Dust must be avoided, and the waste material must be disposed of as radioactive waste from other operations. Sometimes the old compound is soaked off; where this is done, the hands should not be permitted to come in contact with the solvent after dials have been immersed in it. The rubber gloves used for protecting the hands should be checked frequently for radioactive contamination.

Dressing Rooms and Protective Clothing. In plants manufacturing radioactive luminous dials there is absolute necessity for dressing rooms entirely separate from the workrooms. These dressing rooms are to be used by the employees to change from street clothes to working costume and for storage of personal effects, including purses and other valuables. Employees should be provided with coveralls, such as smocks, and caps, which they never take from the plant. Laundering and testing for radioactivity of these garments should be the responsibility of management. The coverall should be the external garment worn at all times in the plant. A double locker system should be installed, and street clothing should be kept entirely separate from work clothing. All personal effects of the employee should be kept in the locker for street clothing.

B. THORIUM POISONING

1. *Industrial Use of Thorium*

In addition to the former use of mesothorium in radioactive luminous compound, thorium itself is used in the manufacture of gas mantles, which are still in considerable demand in this country, mainly for use in portable gasoline lights and similar lighting devices. In the extraction of thorium from the ore, mesothorium is separated and, usually, refined. The supply of mesothorium is not sufficient in quantity, nor is the regularity of production adequate, to permit it to compete with radium for industrial use. Consequently, there is little demand for this radioactive substance, and the refining of mesothorium has been limited to one or two laboratories with a few employees under close supervision. The large demand for thorium now is as fuel for nuclear reactors, and refining operations are at present supervised by the Atomic Energy Commission. A summary of the hazards and precautions for a laboratory engaged in mesothorium refining has been published by Schlundt, McGavock, and Brown.[18] These hazards are similar, though somewhat intensified in degree, to those described in this chapter in connection with the preparation and application of radioactive luminous compound.

In the thorium mantle industry the main hazards are probably from the inhalation of thoron in the mantle-soaking operations, where mantles are soaked in open bowls of thorium nitrate solution, and from the inhalation of dust in the mantle-cutting operation, where considerable thorium-bearing dust is generated. Both operations can be controlled by local exhaust ventilation. Concentrations up to 4×10^{-9} curie of thoron per liter of air have been found in this industry by Evans and Goodman,[19] but none of the workers studied showed evidence of injury or of storage or excretion of thorium or its radioactive products. The chief difference between this situation and those where materials containing radium are manipulated, as far as measurements for control are concerned, lies in the methods of measuring the radioactive gas, thoron, the counterpart of radon in the radium family, by means of its radiation. Different methods are required because of the very short half-life of thoron. The inhalation of thoron or the ingestion of substances containing mesothorium will have the same general consequences physiologically as the inhalation or ingestion of equivalent amounts of radon or radium.

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[18] H. Schlundt, W. McGavock, Jr., and Mildred Brown, *J. Ind. Hyg.*, **13**, 117 (1931).

[19] R. D. Evans and C. Goodman, *J. Ind. Hyg. Toxicol.*, **22**, 89 (1940).

2. Tolerances

The tolerances for exposure to the gamma rays of the thorium family of radioactive isotopes and to thoron in the atmosphere, as well as the tolerance for thoron in the expired breath of the employees, are the same as for radium and radon given in preceding sections. The gamma radiation is measured in roentgens, and the thoron in curies per liter.

3. Methods for Measurement of Thoron

Because the radioactive gas, thoron, has a much shorter period of existence after removal from the source than has radon, decaying to half value in about 55 seconds, a different procedure must be used to determine thoron. It is obviously impossible to collect it in a sample of air and send it to a central laboratory for measurement. One procedure is to measure the thoron at the plant by circulating the air containing it through a system such as described by Schlundt and his coworkers[18] and shown schematically in Figure 7.

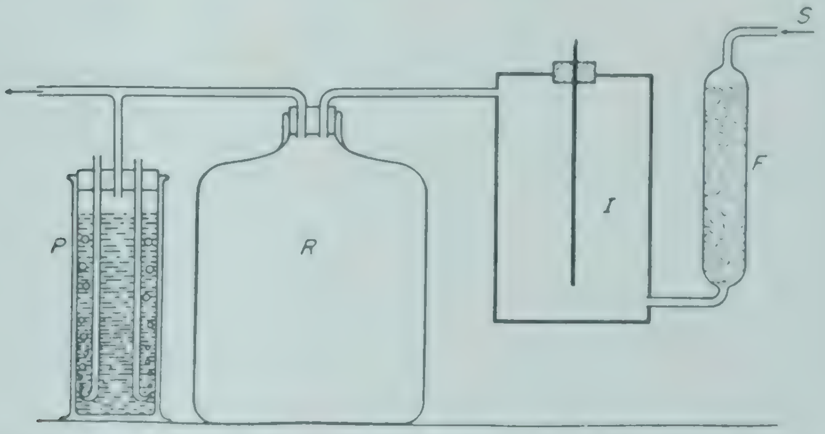

Figure 7. Diagram of system for measuring the thoron content of air by circulating it through an ionization chamber. *P*, constant pressure device; *R*, gas reservoir; *I*, ionization chamber; *F*, filtering and drying tube; *S*, air inlet.

An alternate procedure, particularly convenient for testing room air, is described by Evans and Goodman.[19] In this method the radioactivity from the thoron is deposited on a metal disk and sent to a central laboratory for measurement, from which the thoron content of the air can be computed. The principle of the methods rests on the fact that thoron decays rapidly into a solid, thorium-A (Po^{216}), which has a much briefer existence, decaying in turn into thorium-B (Pb^{212}), which has a half-life of 10.6 hours. As a radioactive isotope of lead, thorium-B is also a solid that may be collected on a metal disk and the disk sent to a laboratory equipped to measure the alpha and beta rays emitted from this deposit. The more powerful ionizing effects of the alpha rays make them more suitable for use in this measurement. An apparatus to collect thorium-B is shown schematically in Figure 8. This equipment can be made readily portable. The collector disk, *D*, is mounted in a stream of the air to be tested. This disk is held at a high negative potential with respect to the inner metal surface of the collecting chamber. Since the thorium A and thorium B atoms are present as positive ions they are driven to the metal disk by this arrangement.

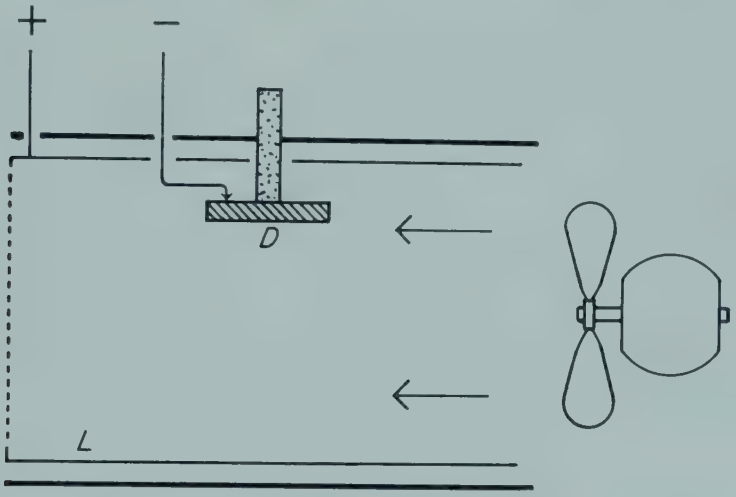

Figure 8. Diagram of arrangement for accumulating the radioactive deposit from thoron in the atmosphere of a workroom. *D,* disk on which deposit is accumulated; *L,* electrically charged cylinder, which creates the electric field to drive ThB atoms to *D.*

4. Protective Rules for Handling Thorium

As has been indicated, the precautions required in handling large quantities of thorium are quite similar to those required in the radium dial-painting industry, after making allowance for the different nature of the manipulations involved. These may be briefly summarized as meticulous care in handling the material to prevent general contamination of the workrooms and equipment, plus adequate ventilation to reduce the thoron concentration in the air to the required level.

If material containing mesothorium in a concentrated form is accumulated as a part of the process of refining the thorium, the same precautions must be adopted as for handling equivalent amounts of any other radioactive isotope. Because the gamma rays from mesothorium extend to higher energies than those from a preparation of radium, and are consequently more penetrating, thicker shields must be used to screen off the gamma rays of mesothorium. It is essential that gamma-ray measurements be made to test such shielding to ensure that the intensities are reduced to tolerance levels for this type of radiation.

Handbooks of the National Bureau of Standards on Radiation Protection

Title	Handbook No.	Year
Radium Protection	23	1938
Safe Handling of Radioactive Luminous Compound	27	1941
Medical X-ray Protection Up to Two Million Volts	41	1949
Safe Handling of Radioactive Isotopes	42	1949
Recommendations of the International Commission on Radiological Protection	47	1950
Control and Removal of Radioactive Contamination in Laboratories	48	1951
Recommendations for Waste Disposal of P^{32} *and* I^{131} *for Medical Users*	49	1951
X-ray Protection Design	50	1952
Radiological Monitoring Methods and Instruments	51	1952
Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water	52	1953
Recommendations for the Disposal of C^{14} *Wastes*	53	1953
Protection Against Betatron-Synchrotron Radiations up to 100 Million Electron Volts	55	1954

CHAPTER XX

Lighting for Seeing

SYLVESTER K. GUTH AND E. A. LINSDAY

To provide the best working conditions it is necessary to control all the environmental factors that influence human performance and efficiency. Important among these factors are light and lighting that enable workers to see quickly, accurately, comfortably, and safely. Even in this era of mechanization and automation there are few industrial operations that are not ultimately dependent upon an employee's ability to see.

The specification of light and lighting must be founded upon as sound a basis as possible. Human behavior, performance, and achievement are the end results of seeing. Therefore, it is necessary to evaluate light and lighting not only in terms of speed and accuracy of visual performance, but also in terms of physiological and psychological effects upon human beings. With this in mind, an expanded concept of *over-all* human efficiency has been developed[1,2] and is being applied to modern lighting practice. The older and, unfortunately, still very prevalent viewpoint of human efficiency considers only the useful work done per hour or per dollar. No thought is given to the *total* human energy expended in performing the work. This narrow viewpoint ignores consideration of wear and tear on eyesight and other parts of the worker, waste of various kinds of human energy and other human resources, and, to a large extent, human reserve resources.

Figure 1 is a simplified diagram to illustrate the expanded concept of human efficiency. The lower curve represents the improvement in production by a worker performing a task when the level of illumination is increased. In general, the rate of working increases rapidly as the amount of light is increased from a relatively low level. Although the curve tends to flatten out, it does continue to rise slowly as the footcandle level is increased to very high values. On the narrow basis of useful work done, the efficiency of the worker would be represented by a point on this curve. For ordinary tasks involving details considerably above the threshold of size and contrast, such as this printed page, the rate of performance of useful work may reach an optimum at levels of illumination of 10 or 20 footcandles.

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[1] M. Luckiesh and F. K. Moss, The new science of seeing, *Trans. Illum. Eng. Soc.*, **23**, 15 (1930).

[2] Many of the references cited include extensive bibliographies on specific aspects of light, vision, and seeing.

Thus, the optimum level of illumination for such a task would be considered as 10 or 20 footcandles. Obviously, for other more difficult industrial tasks the optimum footcandle level will be considerably higher.

As the level of illumination is increased above the optimum, the task becomes easier to perform even though production of useful work may not increase appreciably. Less useless energy is expended by the worker. This is illustrated by the upper broken line curve of Figure 1. Obviously, when seeing is extremely difficult we must call upon a large portion of our resources that are involved in seeing. As seeing becomes easier, our reserve resources increase and the nonproductive work decreases. Thus, the worker becomes a far more efficient human seeing machine at levels of illumination well above those that will permit him to perform at an optimal rate. In other words, a truer index of over-all human efficiency is the ratio of the resources expended in useful work to the total resources expended in useful and useless work. Tangible benefits from applying this broader concept include greater safety, decreased spoilage and rework, decreased fatigue, improved morale, lower labor turnover, and so forth.[3,4]

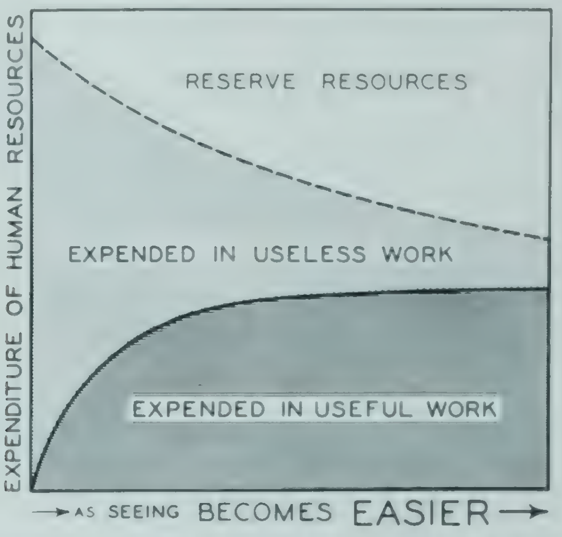

Figure 1. A diagrammatic view of the expanded concept of lighting and seeing. Even after production ceases to improve appreciably, seeing becomes easier and fewer human resources are expended in performing useless work. The true measure of human efficiency is the ratio of resources expended in useful work to the total expended in useful and useless work.

I. Lighting Terms and Units

There are many terms and units used in illuminating engineering.[5] However, it is only necessary to have a clear understanding of certain basic ones.

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[3] H. Kuhn, *Eyes and Industy*. Mosby, St. Louis, 1950.

[4] Value of good lighting in war production (Committee Report). *Trans. Illum. Eng. Soc.* **38,** 13 (1943).

[5] Illuminating Engineering Nomenclature and Photometric Standards. Z7.1-1942. American Standards Association, New York, 1942.

The *lumen* is the unit of luminous flux emitted through a unit solid angle (steradian) from a uniform point source of one candle. It is used to represent the total light output of light sources.

Candlepower is luminous intensity expressed in candles. An ordinary candle about an inch in diameter produces about one candle in a horizontal direction.

Illumination is the density of light flux incident upon a surface.

The *footcandle* is the unit of illumination when the foot is the unit of length. It is the illumination on a surface, one square foot in area, on which is uniformly distributed a flux of one lumen. It equals one lumen per square foot.

Photometric brightness, or *luminance*, is a measure of the light emitted by a luminous body or reflected from a surface. It may be expressed in terms of the lumens being emitted or reflected from a perfectly diffusing source. The term brightness, alone, usually refers to the sensation that results from viewing surfaces from which light comes to the eye; it often is used interchangeably with luminance, since the context usually indicates whether the sensory or photometric meaning is intended.

The *footlambert* is the unit of photometric brightness and is equal to the uniform brightness of a perfectly diffusing surface emitting or reflecting one lumen per square foot. The brightness in footlamberts is equal to the illumination on a surface multiplied by its reflectance.

Reflectance is the ratio of light reflected by an object to the incident light.

II. Visibility

Not all things that can be seen are equally visible. Many factors combine to make details visible and recognizable, but four of them may be considered as fundamental characteristics of visual tasks.[6] Perhaps the most obvious one is the visual *size* of an object expressed in terms of visual angle. A telephone pole is physically large, yet when viewed from a long distance its apparent size is small. Visual acuity is a measure of the sensitivity of the eye in terms of the size threshold. It is equal to the reciprocal of the angular size in minutes of the critical detail that can be just barely seen.

The *contrast* between the details of an object and their immediate background has a considerable bearing on visibility. For a given set of conditions, visibility is highest when contrast is at a maximum. Black print on white paper is much more visible than the same print on a dark gray paper.

Many industrial tasks involve motion. Thus, *time* is an important factor. The speed of a moving object must be slow enough that the eye can take a visual snapshot or follow its movement. The spokes of a rapidly rotating wheel appear blurred, but when it is turned slowly, accurate visual impressions can be registered.

The fourth fundamental factor is *brightness*. Without brightness, sight would be impossible, all objects would remain invisible, and, in effect, we should be blind.

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[6] P. W. Cobb and F. K. Moss, Four fundamental factors in vision, *Trans. Illum. Eng. Soc.*, **23**, 496 (1928).

Considerable research has provided us with comprehensive data on the relationships among these four fundamental factors.[6,9] Figure 2 illustrates how contrast and size vary for three brightness levels. The curves represent the borderline between visibility and invisibility. Small objects must have high contrasts in order to be seen and, conversely, low-contrast objects must be relatively large in size. As the brightness level is increased, either the size or the contrast, or both, may be decreased. Similarly, when considerable time is available for seeing, objects can be small in size or low in contrast. However, in the case of many typical visual tasks, size, contrast, and time are generally fixed. Therefore, it is apparent that the most universally controllable factor is brightness.[10] Increased brightness is obtained by higher footcandle levels.

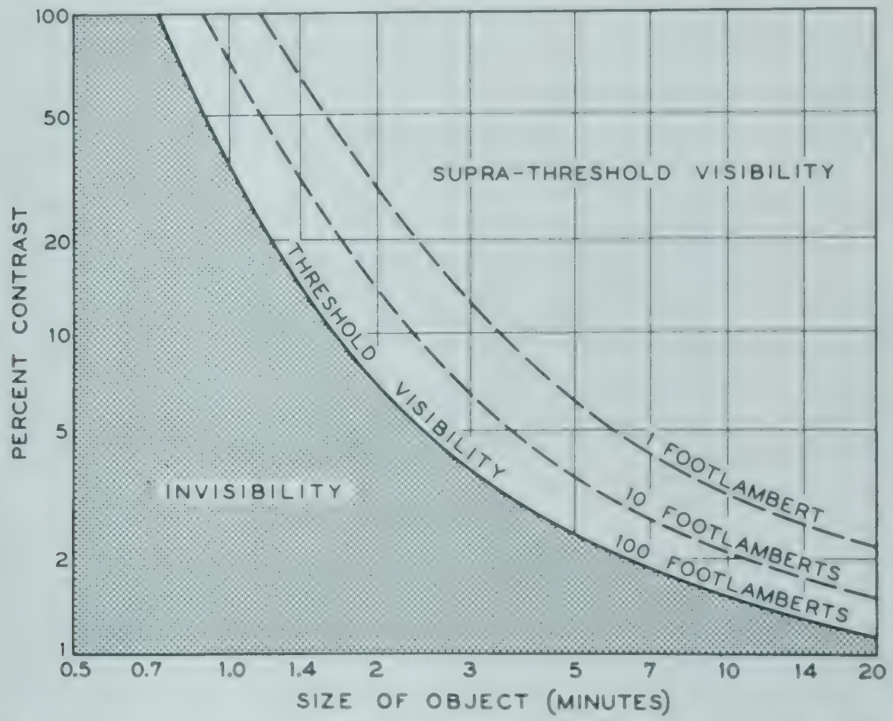

Figure 2. The relationships among size, contrast, and brightness. The invisible region shrinks as the brightness level is increased.

A familiar method of presenting data on the effectiveness of illumination is in

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[7] H. R. Blackwell, Brightness discrimination data for the specification of quantity of illumination, *Illum. Eng.*, **47**, 602 (1952).

[8] H. C. Weston, *The Relation between Illumination and Visual Efficiency—The Effect of Size*, Joint Report on Industrial Health Board and Illumination Research Committee, Report No. 47-105, H. M. Stationery Office, 1935.

[9] H. C. Weston, *The Relation between Illumination and Visual Efficiency—The Effect of Brightness Contrast*, Medical Research Council, Industrial Health Research Board, Report No. 87, H. M. Stationery Office, 1945.

[10] M. Luckiesh, *Light, Vision and Seeing*. Van Nostrand, New York, 1944.

terms of visual acuity, or the ability to distinguish fine details. Some typical results are shown in Figure 3 for black objects viewed against white and gray backgrounds.[11] The relative visual acuity obtained with a black-on-white test object and 10 footcandles is assigned the value of 100 per cent. However, it must be remembered that the majority of industrial tasks are not black on white, but range from light gray-on-white to dark gray-on-black. Thus, the right side of Figure 3 is particularly significant. With 10 footcandles, if the contrast is decreased from 96 to 63 per cent, visual acuity is reduced about 34 per cent. In other words, for a given footcandle level a larger object is required for lower contrasts. Even with 100 footcandles, the relative visual acuity with the lower-contrast test object is 12 per cent less than that obtained with 10 footcandles on a black and white task. Thus, if visual acuity is to be used as a basis for prescribing illumination, it is necessary to have data for a wide variety of contrasts.

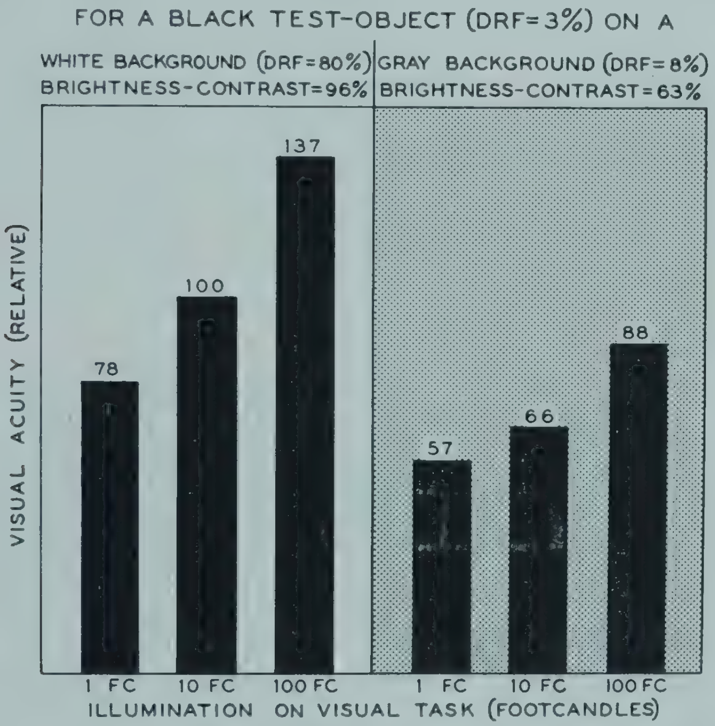

Figure 3. The contrast between an object and its immediate background is an important, but often neglected, factor in visual acuity. For a given footcandle level, visual acuity is considerably less when the contrast is low (DRF = diffuse reflection factor).

Similar results are obtained when speed of reading is the criterion. In Figure 4 are presented data obtained while reading black-on-white (curve *b*) and black-on-gray (curve *a*) printed material.[12] The reflectances of the papers were 80 and 23 per cent, respectively. The speed of reading was much less for the print on gray paper. However, in order to emphasize the difference in the shapes of the two curves, they have been arbitrarily crossed at 4 footcandles. The speed of reading the high-contrast reading matter does not increase appreciably beyond about 16 footcandles, but there is no indication of an optimum speed of reading for the low-contrast reading matter in the same range of footcandles. When the illumination was increased from 4 to 20 footcandles, the rate of reading the low-contrast material increased almost 60 per cent, whereas the rate for the high-contrast material increased only 17 per cent.

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[11] M. Luckiesh, Visual acuity and visual tasks, *Illum. Eng.*, **39**, 415 (1944).

[12] M. Luckiesh, A. H. Taylor, and R. H. Sinden, Data pertaining to visual discrimination and desired illumination intensities, *J. Franklin Inst.*, **192**, 757 (1921).

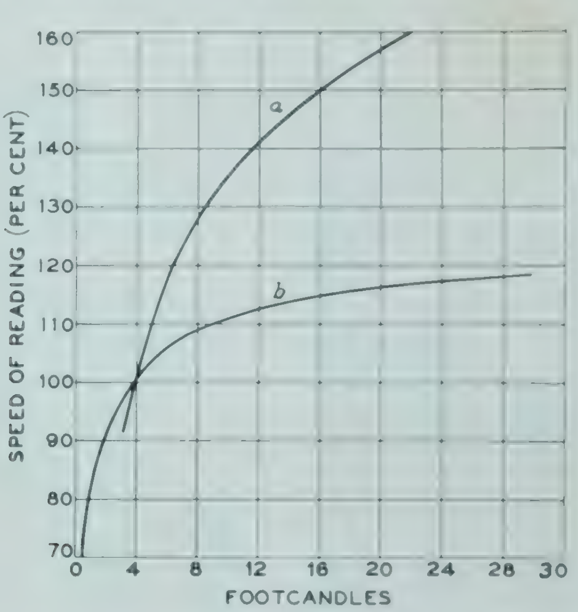

Figure 4. Speed of reading depends upon the contrast between the ink and the paper. Curve *b* is for black print on white paper and curve *a* is for black print on gray paper. The two curves have been arbitrarily represented as 100 at 4 footcandles to show the relatively greater increase in speed for the more difficult task, *a*.

The limited available data on a number of typical workworld tasks show that higher levels of illumination are significantly effective in improving speed and accuracy of working.[13] [16] For example, the speed of reading a steel vernier rule to .001 inch continued to increase up to 200 footcandles with no indication that an optimum had been reached. The speed of discrimination of small brass-on-steel and steel-on-brass objects increased with levels of illumination up to 100 footcandles (the maximum available) with no leveling off. In other words, when difficult, small, low-contrast tasks are involved, several hundred footcandles are required for optimum visual performance.

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[13] C. E. Ferree and G. Rand, Intensity of light and speed of vision with special reference to industrial situations. Parts I and II. *Trans. Illum. Eng. Soc.*, **22**, 79 (1927), and **33**, 507 (1928).

[14] M. Luckiesh and F. K. Moss, Light, vision and seeing, *Ind. Med.*, **7**, 636 (1938).

[15] Lighting for woolen and worsted textile mills (Report of Joint I.E.S.-A.S.M.E. Committee on Lighting in the Textile Industry), *Illum. Eng.*, **44**, 364 (1949).

[16] H. R. Blackwell, *Illum. Eng.*, **47**, 605–606 (1952).

Visual acuity and speed of reading can be considered as indicators of precision of seeing and production, respectively. Ideally, if all workworld tasks could be studied in the laboratory, it would be possible to determine the footcandle level that will permit the worker to achieve optimum performance. That is, curves such as shown in Figures 2 and 4 could be obtained for each task. Since this is impractical, it is necessary to devise a method by which typical tasks can be visually appraised and related to fundamental laboratory data.

The unaided human being cannot make accurate measurements. All he can do is judge qualitatively that things are hot or cold, soft or hard, and so forth. Instruments and measuring techniques are necessary. An instrument that has been found to be extremely useful is the Luckiesh-Moss Visibility Meter,[17-19] illustrated in Figure 5. Variable density filters are used to reduce a visual task to the threshold of perception and, by means of an appropriate scale, the required filter density is assigned a numerical visibility rating. With this instrument, the visibility level of a task is related to the visibility of standard laboratory test objects viewed under specified conditions. Recent data have shown that these visibility ratings are directly relatable to the absolute threshold of illumination[20] and to the brightness-difference threshold.[21]

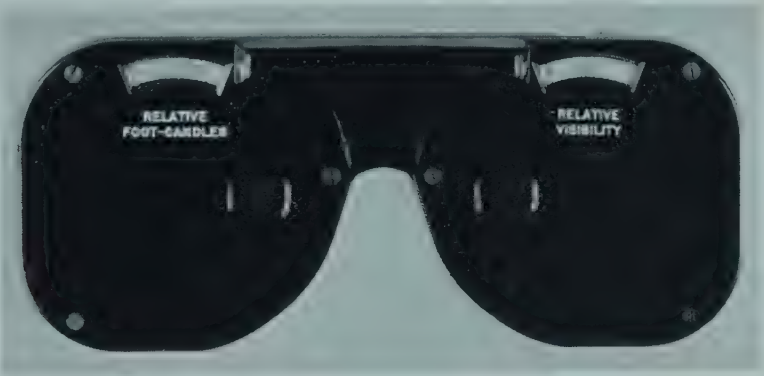

Figure 5. The portable Luckiesh-Moss Visibility Meter. This is a useful instrument for determining footcandles for equal visibility.

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[17] M. Luckiesh and F. K. Moss, Visibility—its measurement and significance in seeing, *J. Franklin Inst.*, **220,** 431 (1935).

[18] M. Luckiesh, A. A. Eastman, and S. K. Guth, Technique of using the Luckiesh-Moss Visibility Meter, *Illum. Eng.*, **43,** 223 (1948).

[19] S. K. Guth, Visibility, *Gen. Elec. Rev.*, **55,** 26 (1952).

[20] M. Luckiesh, S. K. Guth, and A. A. Eastman, A new scale of relative footcandles for the Luckiesh-Moss Visibility Meter, *Illum. Eng.*, **45,** 211 (1950).

[21] S. K. Guth, A. A. Eastman, and R. C. Rodgers, Brightness difference—a basic factor in seeing, *Illum. Eng.*, **48,** 233 (1953).

One logical objective of lighting is to make various objects and visual tasks as nearly equal in visibility as possible. Therefore, a more important application of the L-M Visibility Meter is to determine the footcandles necessary to provide equality of visibility.[22] That is, the levels of illumination are determined with which various visual tasks can just be seen through a given density of the filters. It is widely used to study the visibility of school, office, and industrial tasks. Since it is portable, the instrument can be taken into an industrial area and the task evaluated where it is being performed and under the actual viewing conditions. Table 1 illustrates a few of the results obtained with the L-M Visibility Meter.

TABLE 1

Results Obtained with the Luckiesh-Moss Visibility Meter

Task	Footcandles for equal visibility
Reading	
Typing on white paper	15
Magazine text	30
Newspaper text	60
Handwriting in pencil	60
Shorthand notes	90
Bookkeeping	120
Drafting	120
Medium grade assembly and inspection	200
Metal buffing	250
Sewing, white thread on white cloth	300
Metal finishing—surface grinding	500
Sewing, black thread on black cloth	over 1000
Precision die making	over 1000

Some of the tasks require what appear to be unreasonably high levels of illumination. For example, drafting requires eight times as much light as reading typing on white paper, and the industrial tasks require still more. When the tasks are analyzed in terms of size, contrast, and time, it is evident that such footcandle levels are required in order for the tasks to be equal in visibility. Furthermore, the values are in agreement with experimental results such as shown in Figures 3 and 4. The footcandle levels should be considered as relative rather than recommended levels of illumination for the performance of these visual tasks. It is obvious that the more difficult, low-contrast tasks require considerably higher footcandle levels than the larger, high-contrast tasks. In the present discussion, the practicability of attaining these higher footcandle levels is not of importance. The interest of the illuminating engineer lies in developing a single standard for lighting practice. It does not seem logical that light for seeing industrial tasks should be recommended on a different basis than for office tasks just because it may be more difficult to obtain. Visibility does provide a uniform basis for evaluating different tasks and for determining the amount of light needed. Many industrial tasks have been studied in this manner and the results used to determine recommended footcandle levels.[23]

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[22] M. Luckiesh and A. A. Eastman, Footcandles for critical seeing. *Illum. Eng.*, **41**, 82 (1946).

III. Ease of Seeing

Providing light for perception is only part of the over-all problem. The eye is but a single unit of the entire human organism. It is influenced by body fatigue and, also, it influences general body fatigue. Unfortunately, fatigue is difficult to define because of the innumerable factors concerned.[24] It is important to adjust all the environmental factors so that they combine to provide the best possible working conditions. Therefore, in the case of seeing, the footcandle level should be high enough that the worker can perform his job for prolonged periods with minimum expenditure of energy.

Many attempts have been made to detect and appraise visual fatigue by measurements of visual functions, such as visual acuity, speed of perception, and visibility. Even where work periods were long and the workers expressed definite indications of fatigue and discomfort, the decrement in such functions generally has been insignificant. Therefore, it has been necessary to explore the possibilities of other more sensitive criteria that will more adequately evaluate poor seeing conditions.

Some of the results obtained with more sensitive criteria based upon certain involuntary responses are presented in Figure 6 for three levels of illumination.[25] In all of these investigations the visual task of reading a well-printed book was performed by young adult subjects possessing average normal vision. Thus, the results may be considered conservative, since greater differentials certainly could be expected from older subjects or those having subnormal eyesight.

The data summarized in Figure 6 relate directly to ease of seeing as appraised by the integrated physiological effects of visual effort. The close correlation among these criteria indicates that the favorable influences of illumination upon the visual processes and upon ease of seeing extend to levels of illumination at least as high as 100 footcandles. Since the pages in all cases were white, this is equivalent to saying that increased visual benefits are obtained for brightness levels at least as high as 100 footlamberts. Studies of this sort indicate that the broader concept illustrated in Figure 1 is sound. If the task of reading involved a gray surface (such as that used for obtaining curve *a* of Figure 4), several hundred footcandles would be required to produce the same brightness conditions and ease of seeing illustrated in Figure 6. The relative footcandles for equal visibility shown in Table 1 are in agreement with this. In other words, dark, low-reflectance tasks can be given a reasonable visibility level and can be performed with relative ease if higher levels of illumination are made available. However, these added footcandles will not produce excessive brightnesses because of the inherently low reflectances of these more difficult tasks.

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[23] American Standard for Industrial Lighting, A11.1-1952. American Standards Association, New York, 1952.

[24] S. H. Bartley and E. Chute, *Fatigue and Impairment in Man*. McGraw-Hill, New York, 1947.

[25] M. Luckiesh and F. K. Moss, *The Science of Seeing*. Van Nostrand, New York, 1937.

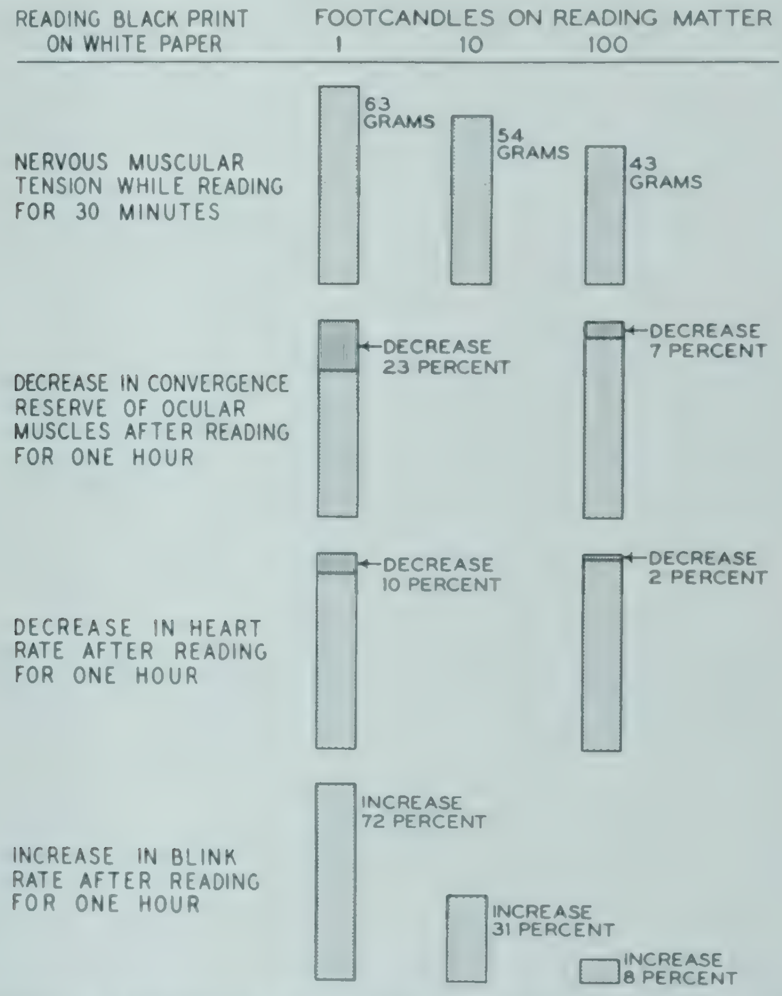

Figure 6. A summary of the results of several researches relating to ease of seeing as evaluated by four of the effects of visual effort.

IV. Quality of Lighting

As the brightness of a visual task is increased by higher footcandle levels the eyes become more sensitive in their ability to see. It follows that if they are more sensitive foveally, they should become more sensitive peripherally. Therefore, the quality of lighting—the distribution of light upon the task and its surroundings and the distribution of brightness throughout the visual field—becomes increasingly important. Our tolerance of brightness in areas outside of the task area decreases as footcandles go up.[26] [28] These brightnesses and the relationships among them contribute favorably or unfavorably to the seeing conditions. They may influence the visibility of the task or they may result in decreased ease of seeing. Brightness and color are primary factors in perception, and brightness contrast is very generally of major importance in the visibility and recognition of details of objects. In other words, within the visual task, brightness contrast is a favorable factor in seeing. However, when the brightness of the central field or visual task differs greatly from that of the surrounding field, unfavorable effects on seeing are produced. Large brightness variations in the peripheral field also are undesirable. In this respect, brightness contrast is an unfavorable factor in seeing.

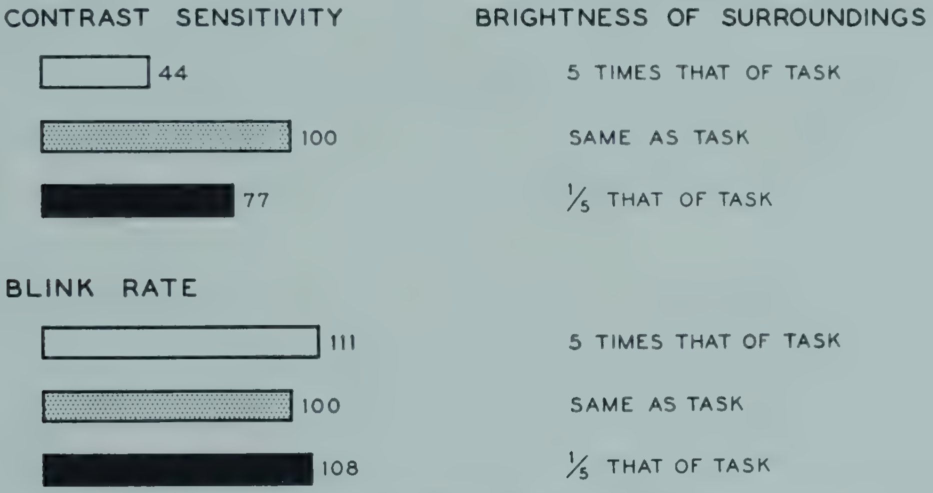

Figure 7. The effects of brightness of surroundings upon contrast sensitivity and blink rate, indicating the desirability of uniformity of brightness.

In Figure 7 are shown the effects of the brightness of surroundings upon contrast sensitivity[29] (ability to see) and blink rate[30] (ease of seeing). Sensitivity of the visual sense is greatest when the brightness of the surroundings is the same as that of the task. Similarly, ease of seeing is optimum when the work and surround brightnesses are the same. Studies of visual acuity[31] and precision of seeing[32]

[26] P. G. Nutting, Effects of brightness and contrast in vision, *Trans. Illum. Eng. Soc.*, **11,** 939 (1916).

[27] L. L. Holladay, The fundamentals of glare and visibility, *J. Opt. Soc. Amer.*, **12,** 271, (1926).

[28] W. Harrison, What is wrong with our 50-footcandle installations?, *Trans. Illum. Eng. Soc.*, **32,** 208 (1937).

[29] P. W. Cobb, The effect on foveal vision of bright surroundings—IV, *J. Exptl. Psychol.*, **1,** 540 (1916).

[30] M. Luckiesh and F. K. Moss, Brightness contrasts in seeing, *Trans. Illum. Eng. Soc.*, **34,** 571 (1939).

[31] R. J. Lythgoe, The Measurement of Visual Acuity, Special Report No. 173, Medical Research Council, H. M. Stationery Office, London, 1932.

[32] P. W. Cobb and F. K. Moss, The effect of brightness on the precision of visually controlled operations, *J. Franklin Inst.*, **199,** 507 (1925).

substantiate these results. Investigations have shown that these brightness relationships between a task and its surroundings are of greatest importance within about a 60-degree zone around the line of vision.

Another cause of visual impairment and discomfort is the brightness of more remote areas such as lighting equipments. Extensive investigations[33] [35] have shown that large areas of even apparently moderate brightnesses are disturbing and produce discomfort even when located at considerable angular distances from the normal line of vision. Factors such as size, position, and brightness of source, and the adaptation or field brightness, all are important. In Figure 8 are illustrated the relative effects of these factors and how they must be balanced so that the work area will be visually comfortable. When sources of brightness are located near the line of vision (indicated by the horizontal line), they must be small in size or low in brightness. As they are moved farther from the task area, size and brightness may be increased, as shown by the values in and above the circles. The combined effects are shown by the circles on the broken line, which is for a constant position index.[36] In order to maintain a constant visual sensation as area is

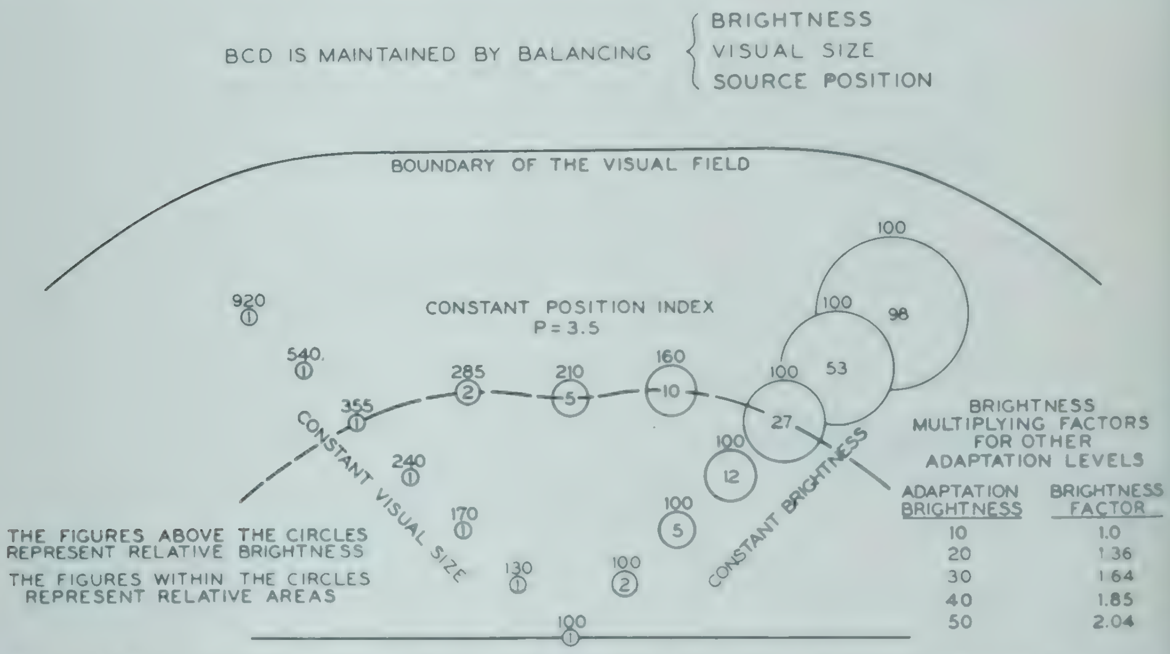

Figure 8. The relative effects of size, brightness and location of a source of brightness upon visual comfort (BCD = borderline between comfort and discomfort).

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[33] M. Luckiesh and S. K. Guth, Brightnesses in visual field at borderline between comfort and discomfort (BCD), *Illum. Eng.*, **44**, 650 (1949).

[34] S. K. Guth, BCD brightness ratings in lighting practice, *Illum. Eng.*, **47**, 184 (1952).

[35] P. Petherbridge and R. G. Hopkinson, Discomfort glare and the lighting of buildings, *Trans. Illum. Eng. Soc. (London)*, **15**, 39 (1950).

[36] Position index is an indicator of how much the brightness of a source may be increased as it is moved from the line of vision in order to maintain a constant visual sensation.

increased from relative values of 1 to 27, relative brightness must be reduced progressively from 355 to 100. For larger areas, the brightness must be decreased at an even greater rate. The table in the lower right corner of Figure 8 illustrates how the source brightness may be increased for higher adaptation brightnesses. Thus, if adaptation brightness is doubled (corresponding to a doubling of the footcandle level) the source brightness may be increased by only one third. Methods have been proposed for evaluating the comfort of lighting systems and are being used for design purposes.[37]

Seeing is a dynamic activity of human beings. Since a worker may look at any part of a visual environment, it is important to eliminate extremes of brightness or darkness. If they are not eliminated, the worker's eyes must continually be adapting to a greatly changing brightness pattern. Fatigue and ease of seeing studies have shown that pupil diameter,[38] precision and rate of working,[39] and blink rate[30] are adversely affected by improper brightness relationships.

V. Color

The subject of light and color[40] is large and complex. However, it is not as mysterious as some people try to make it. While spectral quality of light is important in some visual situations, it is generally of secondary importance in visibility and seeing. So-called white light ranges from a yellowish white with tungsten-filament lamps to a bluish white with daylight fluorescent lamps. All of them are suitable for general lighting use. No real practical advantage has been demonstrated for any one over another. Footcandle level and brightness are of paramount importance.

For specialized tasks involving color discrimination, lamps emitting all colors must be used. A wide range of fluorescent lamps now is available. Those designated as *de luxe* provide balanced spectrums and have been found completely satisfactory for color-critical work. For other tasks, relatively saturated color of light can be used to enhance the contrast within the task. In such cases the color of the light should be complementary to the surface color.

Color of light also is useful for creating a warm or cool atmosphere. This has been found to be particularly desirable to help counteract the effects of hot or cold industrial operations and to create a more livable environment.

VI. The Human Element

All researches in seeing must of necessity involve the human element. However, in most cases differences among individuals are submerged in averages.

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[37] O. P. Meaker and R. L. Oetting, Visual comfort index and tables—their meaning and use in lighting design, *Bulletin* **LS-108,** Lamp Division, General Electric Co., October, 1953.

[38] M. Luckiesh and F. K. Moss, Size of pupil as a possible index of ocular fatigue, *Am. J. Ophthalmol.,* **16,** 393 (1933).

[39] M. Luckiesh and F. K. Moss, The rate of working on alternating fields of different brightnesses, *J. Franklin Inst.,* **200,** 731 (1925).

[40] A. H. Taylor, The nature and causes of small color differences in industry, *J. Opt. Soc. Amer.,* **32,** 651 (1942).

Recent studies of visual comfort and visibility have shown that persons vary considerably. Some are very sensitive to brightness and find that what may be a comfortable situation for others is considerably annoying and uncomfortable to themselves. In Figure 9 is shown the range of brightness judged to be at the borderline of comfort and discomfort,[34] as selected by each of a group of 50 observers. The number of observers selecting borderlines falling within each range is given at the top of the column. The average brightness selected was 890 footlamberts. However, if this were used as the basis for determining brightness limitations, 50 per cent of the observers would be uncomfortable. In other words, a much lower source brightness must be used if all observers are to be comfortable.

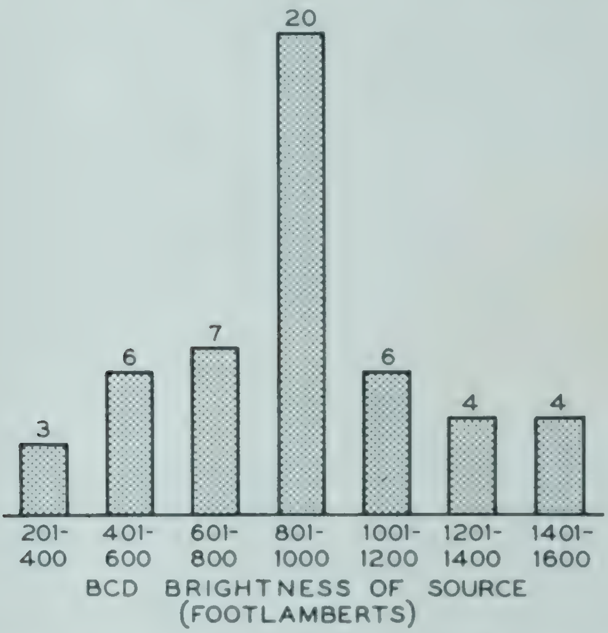

Figure 9. The brightness judged to be at the borderline between comfort and discomfort, as selected by each of a group of observers. Some individuals are much more sensitive to brightness than others.

Even though they may have so-called normal vision, some individuals require three or more times as many footcandles as others to obtain the same visibility level.[41] This is illustrated in Figure 10 in which are plotted the footcandles required by various percentages of observers for several visibility levels. Thus, 50 per cent of the observers will obtain a visibility level of 5 with 30 footcandles. However, about 90 footcandles are needed if at least 95 per cent of the observers are to be able to have the desired visibility level. These data are for high-contrast printed matter. Nevertheless, they do show that many people require more lig than others. It has been shown that older workers often require much more light than younger workers.[42]

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[41] S. K. Guth, Lighting for the forgotten man, *Am. J. Optometry and Arch. Am. Acad. Optometry*, **32**, 413 (1955).

Subnormal vision also will reduce the visibility of an object, and a somewhat higher level of illumination for the desired visibility level will be indicated. Obviously, defective vision should be corrected if at all possible. Nevertheless, many individuals who cannot be given so-called normal vision, can be materially aided by more adequate lighting levels. Thus, their years of productivity can be extended and the employer can continue to take advantage of the considerable training and experience of these workers.

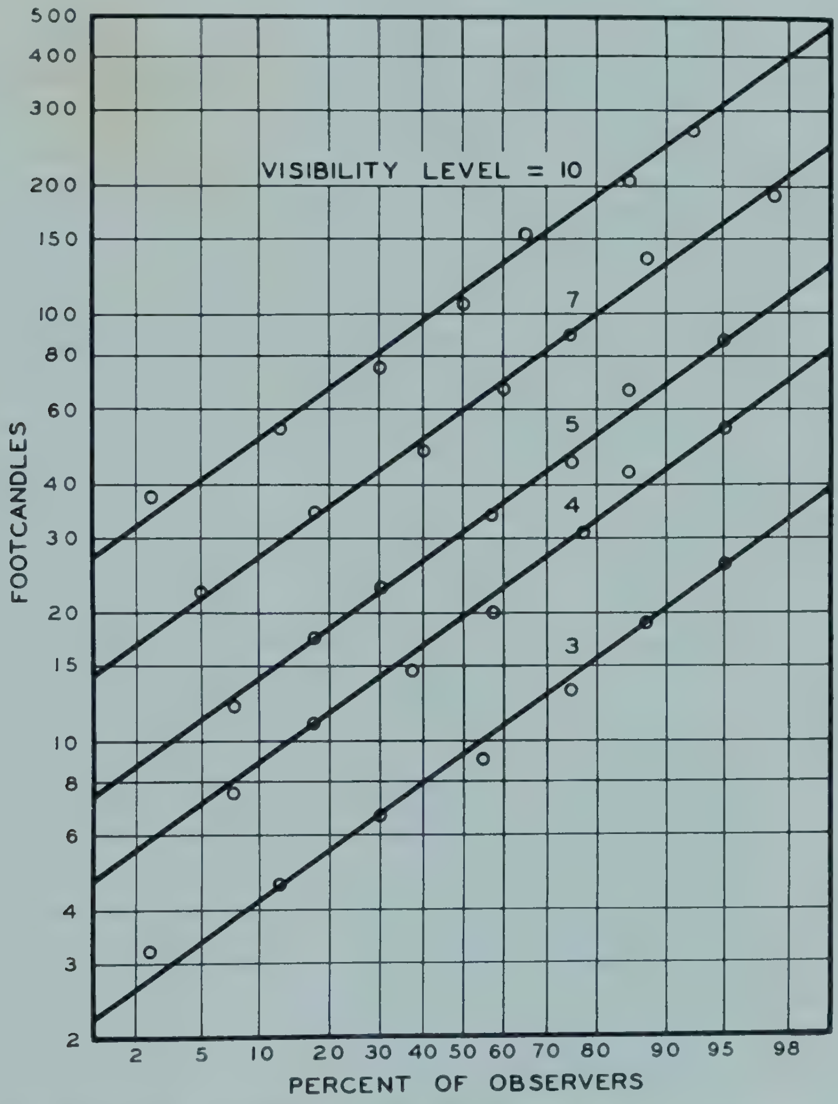

Figure 10. The footcandles necessary for various percentages of observers to obtain given visibility levels.

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[42] H. C. Weston, Age and illumination in relation to visual performance, *Trans. Illum. Eng. Soc.* (*London*), **14**, 281 (1949).

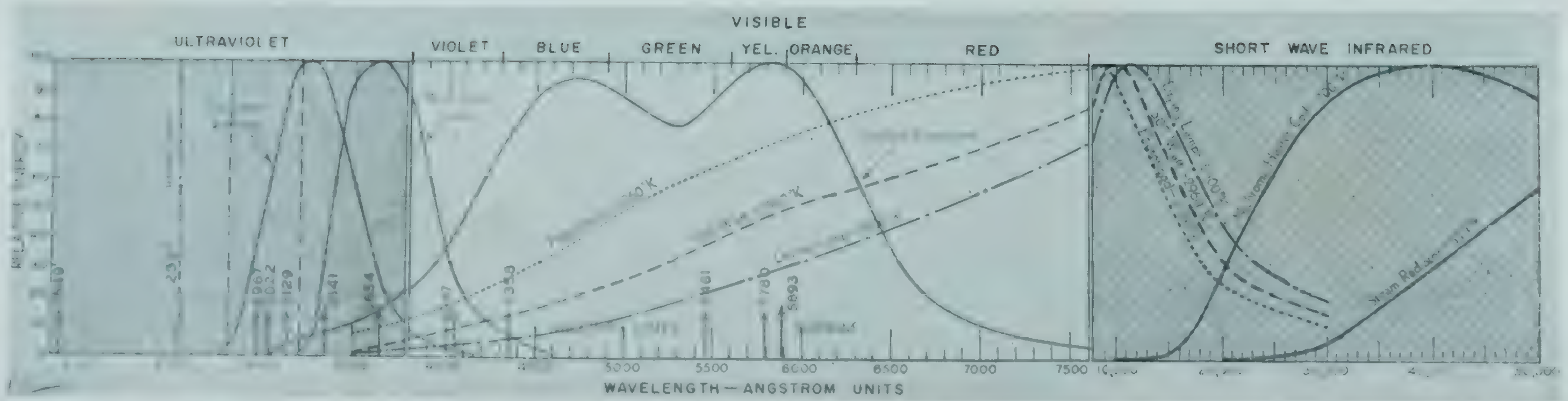

Figure 11 Spectral distribution of lamps. The continuous spectrums of the filament-type lamps peak in the infrared region, and have the highest visible energy (light) at the red end of the spectrum. Fluorescent lamps emit light in all parts of the visible spectrum, the predominance of color depending on the type of phosphor chosen. Mercury lamps radiate at four specific wave lengths in the visible region (noncontinuous spectrum). Color-improved mercury lamps have a phosphor added, which provides red light, lacking in the line spectrum of the straight mercury.

All such factors must be kept in mind when lighting recommendations are made. Economic aspects, of course, are important and may require some compromises. Nevertheless, unless proper weight is given to ease of seeing, visibility, and individual visual capabilities, light and lighting will not be accomplishing the primary purpose of providing quick, accurate, safe, and comfortable seeing.

VII. Light Sources

A. FILAMENT LAMPS

Filament lamps emit essentially black body radiation generated by an electrically heated filament. This radiation is continuous throughout the visible and near infrared regions of the electromagnetic spectrum[43] (Figure 11). The peak radiation is generally in the infrared region, only a portion of the energy being emitted in the visible region as light. Since this peak shifts toward the visible region as the filament is operated at a higher temperature, hotter operation provides a "whiter" light and makes the lamp a more efficient light source. However, it also increases the rate of evaporation of the filament, decreasing the life of the lamp. Therefore, in the design of incandescent light sources, such factors as economics and application of the lamp are considered in determining the most desirable compromise between efficiency and lamp life. For example, where lamps are inexpensive compared to the cost of electrical power, the shorter-life, higher-efficiency lamp should be employed. On the other hand, where lamps are costly or labor costs of replacing them are high, a longer life is more economical. For photographic projection lamp applications, where a large quantity of "white" light is needed, lamps are operated at relatively high efficiency with correspondingly shorter life (5 to 50 hours).

The first practical incandescent electric lamp was developed by Thomas A. Edison in 1879. It consisted of a filament of carbonized thread enclosed in a glass envelope from which the air had been evacuated. Since that date many improvements have been made through active research and development to obtain the incandescent lamp as it exists today. One of these milestones was the development of a filament made of tungsten wire, providing higher efficiency and longer lamp life. Lamp efficiency has been further increased through many developments, including the double and triple coiling of filaments, which reduces heat transfer away from the filament. More recently a new process of "Q-coating" has been devised to give almost perfect diffusion of light from the bulb with no sacrifice in efficiency. Control of light output has been obtained with the introduction of reflector lamps. For these lamps a glass bulb is formed to the desired contour and coated on the inside with a thin film of highly reflecting silver.

B. MERCURY LAMPS

Gaseous discharge lamps were made practical about 1900 with the development of the Cooper Hewitt low-pressure mercury-arc tube. This lamp is the predecessor of the present-day mercury and fluorescent lamps. In general, today's mercury lamps are about twice as efficient generators of light as the filament lamps. However, there are advantages and disadvantages to both that affect the choice of lamp type for any specific application.

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[43] Lamp bulletin, *Bulletin* **LD-1,** Lamp Division, General Electric Co., October, 1950.

High-pressure mercury lamps have the objectionable characteristic of delayed starting and restarting. Several minutes are required for the lamp to reach full brightness, and in case of a momentary power interruption, the lamp will not restart until the arc tube has cooled sufficiently for the mercury vapor to condense —a matter of about 5 minutes. These disadvantages are partly overcome by installing filament lighting along with the mercury, to provide illumination during the brief periods that the mercury lamps are inoperative. One of the most recent improvements in mercury lamps is the addition of a phosphor coating, which converts part of the mercury radiation to light in the red region of the spectrum. When combined with the bluish green light from the mercury arc, color rendition of objects viewed under this source is improved markedly.

C. FLUORESCENT LAMPS

Fluorescent lamps, first introduced commercially in 1938, have become increasingly popular in recent years. Today, more illumination for general lighting purposes is provided by fluorescent lamps than by all other sources combined. The rapid growth of this type of lighting is due in part to the trend toward higher levels of illumination. Fluorescent lamps are about three times as efficient as filament lamps.

Basically, a fluorescent lamp consists of a low-pressure mercury-arc tube through which current flows, causing the mercury vapor to radiate invisible energy.[44] This radiation in turn activates the phosphor coating on the inside of the glass tube, converting this energy to visible light. The lime-glass tube filters out all radiation that would be harmful to the eyes or skin.

Until recently fluorescent lamps were started by means of a starter for each lamp, which heated the electron-emitting cathode in each end of the lamp. More recent developments have made it possible to eliminate this starter switch. Modern fluorescent lamps are started either by ballasts having sufficient voltage to start the lamp instantly or by ballasts having auxiliary windings that heat the cathodes very rapidly to emitting temperature. This latter type of operation is called Rapid Start.

Fluorescent lamp life,[45] unlike filament lamp life, is not limited by lamp efficiency. Consequently, fluorescent lamps are designed to give much longer service (7500 hours). However, lamp life is affected by the number of times the lamp is started. The 7500-hour life rating is based on 3 hours of lamp operation per start. More frequent starting will reduce the life span, whereas lamps will last longer if started less frequently.

D. GERMICIDAL LAMPS

Germicidal lamps are basically the same as fluorescent except that no phosphor is used on the tube. Disinfection of air, water, pharmaceuticals and so forth, with germicidal lamps, is accomplished by making the lamp of a special glass that allows the short-wave ultraviolet energy to irradiate the product. Care should be exercised to avoid exposure of the skin and particularly the eyes to this energy.

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[44] C. L. Amick, *Fluorescent Lighting Manual*, McGraw-Hill, New York, 1942.

[45] R. N. Thayer, Determinants of fluorescent lamp life, *Illum. Eng.*, **49**, 527 (1954).

E. INFRARED LAMPS

Infrared lamps[46] are filament lamps designed to heat areas of the body or to heat products, such as painted surfaces, textiles, and metal parts. Any filament lamp is an efficient source of infrared energy. Infrared lamps are usually designed to have a long life (5000 hours); they are not designed to produce light efficiently.

VIII. Lighting Benefits

The trend in lighting application is continually toward better seeing conditions.[47] With the understanding of the importance of balanced brightnesses[48] and minimized glare in industrial areas, and the development of better techniques of controlling light, higher lighting levels have become practical and highly desirable. Figure 12 shows the increase in illumination levels recommended for indus-

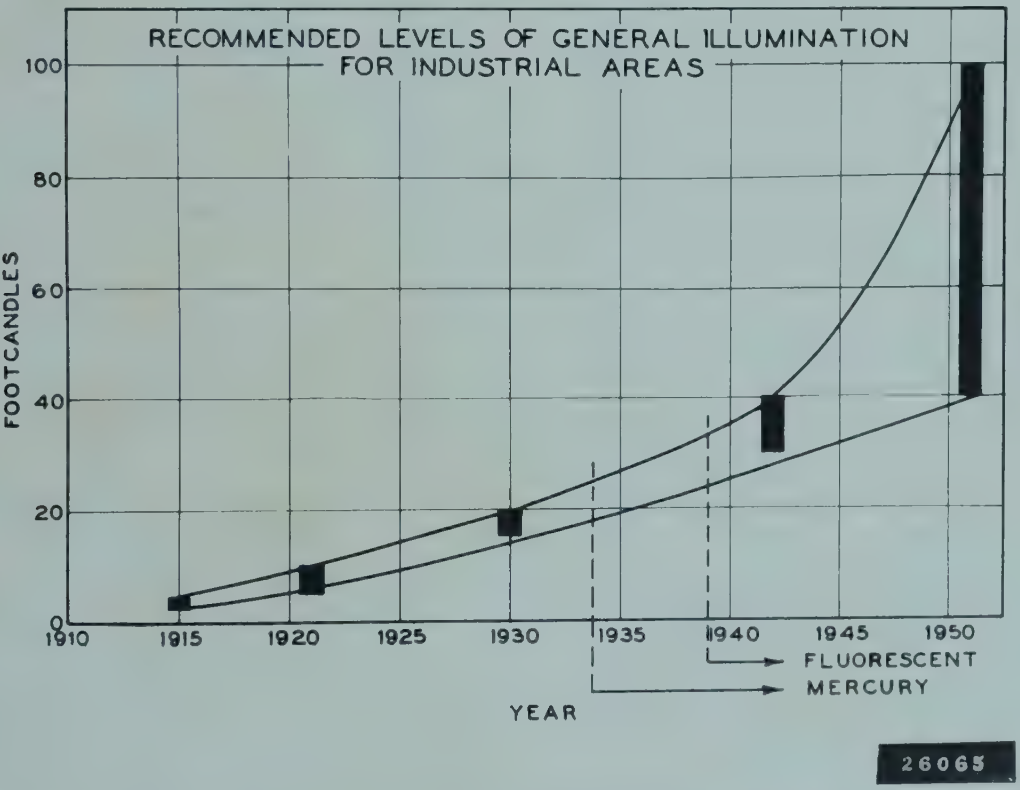

Figure 12. The steady increase in levels of illumination recommended for industrial areas over the past 40 years. Recommendations ranged between the lower and upper solid lines. Broken lines show dates of introduction of new types of lamps.

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[46] C. E. Egeler, Infrared lamps at work. *Magazine of Light*, **20,** 8 (February, 1951).

[47] E. A. Linsday, The industrial lighting look. *Magazine of Light*, **23,** 9 (May–June, 1954).

[48] E. A. Linsday, Revolution in lighting, *Natl. Safety News,* January, 1954.

TABLE 2

Specific Recommended Values of Illumination[a]

	Current recommended practice, footcandles in service (on task or 30 in. above floor)
Airplane manufacturing	
Stock parts	
Production	70
Inspection	150
Parts manufacturing	
Drilling, riveting, and screw fastening	50
Spray booths	50
Sheet aluminum layout and template work; shaping and smoothing of small parts for fuselage; wing sections, cowling, etc.	70
Welding	
General illumination	70
Supplementary illumination	2000
Subassembly	
Landing gear, fuselage, wing sections, cowling and other large units	50
Final assembly	
Placing of motors, propellers, wing sections and landing gear	70
Inspection of assembled ship and its equipment	70
Machine tool repairs	150
Assembly	
Rough	50
Medium	100
Fine	200
Extra Fine	500[b]
Automobile manufacturing	
Assembly line	150
Frame assembly	50
Body manufacturing	
Parts	50
Assembly	50
Finishing and inspecting	300[b]
Bakeries	
Mixing room	30
Face of shelves (vertical illumination)	20
Inside of mixing bowl (vertical mixers)	100[b]
Fermentation room	20
Make-up room	
Bread	30
Sweet yeast raised products	50
Proofing room	20
Oven room	30
Fillings and other ingredients	50
Decorating and icing	
Mechanical	30
Hand	100[b]
Scales and thermometers	50
Wrapping room	30
Storage room	20
Shipping room	30
Reception rooms	20
Washrooms, stairways	20
Halls, corridors, passageways	10
Book binding	
Folding, assembling, pasting, etc.	30
Cutting, punching, and stitching	50
Embossing	50
Breweries	
Brew house	10
Boiling, keg washing, and filling	20
Bottling	30
Building	
Construction	20
Excavation work	5
Candy making	
Box department	30
Chocolate department	
Husking, winnowing, fat extraction, crushing and refining, feeding	20
Bean cleaning and sorting, dipping, packing, wrapping	30
Milling	100
Cream making	
Mixing, cooking, and molding	30
Gum drops and jellied forms	30
Hand decorating	100
Hard candy	
Mixing, cooking, and molding	30

TABLE 2 (*continued*)

	Current recommended practice, footcandles in service (on task or 30 in. above floor)
Die cutting and sorting	100
Kiss making and wrapping	100
Special holiday candy—hand decorating	100
Canning and preserving (from I.E.S. report "Lighting for Canneries")	
Receiving	
Grading raw material samples	20
Tomatoes	100
Color grading (cutting rooms)	100[b]
Preparation	
Preliminary sorting	
Apricots and peaches	50
Tomatoes	100
Olives	125
Cutting and pitting	35
Final sorting	100
Canning	
Continuous belt canning	100
Sink canning	100
Hand packing	20
Olives	50
Examination of canned samples	150[b]
Container handling	
Inspection	150[c]
Can unscramblers	10[c]
Labeling and cartoning	20
Storage warehouses	5
Chemical works	
Hand furnaces, boiling tanks, stationary driers, stationary and gravity crystallizers	10
Mechanical furnaces, generators and stills, mechanical driers, evaporators, filtration, mechanical crystallizers, bleaching	20
Tanks for cooking, extractors, nitrators, electrolytic cells percolators,	50
Clay products and cements	
Grinding, filter presses, kiln rooms	10
Molding, pressing, cleaning and trimming	30
Enameling	50
Color and glazing	50
Cleaning and pressing industry	
Checking and sorting	50
Dry and wet cleaning and steaming	30
Inspection and spotting	300
Pressing	
Machine	50
Hand	100
Receiving and shipping	30
Repair and alteration	300
Cloth products	
Cutting, inspecting, sewing	
Light goods	50
Medium goods	150
Dark goods	500[b]
Pressing, cloth treating (oil cloth, etc.)	
Light goods	50
Medium goods	70
Dark goods	150
Coal tipples and cleaning plants	
Breaking, screening, and cleaning	20
Picking	500[b]
Construction, indoor	
General	20
Corridors	10
Control rooms	
Vertical face of switchboards	
Simplex or section of duplex facing operator	
Type A—large centralized control room 66 inches above floor	100
Type B—Ordinary control rooms at 66 inches above floor	70
Section of duplex facing away from operator	50
Bench boards (horizontal level)	50
Area inside duplex switchboards (horizontal, 1 foot above floor)	10
Rear of all switchboard panels (vertical)	20

(*continued*)

TABLE 2 (*continued*)

	Current recommended practice, footcandles in service (on task or 30 in. above floor)
Emergency lighting, all areas	5
Dairy products	
Fluid milk industry	
Boilers	20
Bottle storage	20
Bottle sorting	70
Bottle washers	500[c]
Can washers	30
Cooling equipment	30
Filling: inspection	70
Gages	70 (on face)
Laboratories	70
Loading platforms	20
Meter panels	70 (on face)
Pasteurizers	30
Receiving room	30
Scales	50
Separators	30
Storage refrigerator	20
Tanks	
Light interiors	30
Dark interiors	150
Thermometer	70 (on face)
Vats	100
Weighing room	20
Dispatch rooms	
Horizontal plane (desk level)	70
Vertical face of board (48 inches above floor, facing operator)	
System load dispatch room	70
Secondary dispatch room	50
Electrical equipment manufacturing	
Impregnating	50
Insulating: coil winding	150
Testing	100
Elevators, freight and passenger	20
Engraving (wax)	200[b]
Explosives	
Hand furnaces, boiling tanks, stationary driers, stationary and gravity crystallizers	10
Mechanical furnaces, generators and stills, mechanical driers, evaporators, filtration, mechanical crystallizers	20

	Current recommended practice, footcandles in service (on task or 30 in. above floor)
Tanks for cooking, extractors, percolators, nitrators	50
Exterior areas	
Boundaries	
Glare projection technique (isolated)	.15 (vertical)
General lighting technique (nonisolated)	.2
Entrances	
Active (pedestrian and/or conveyance)	2.0
Inactive (normally locked, infrequently used)	5
Vital locations or structures	2.0
Building surrounds	.5
Active shipping area surrounds	2.0
General inactive areas	2
Yards (general)	2.0
Loading and unloading plateforms	5.0
Flour mills (from I.E.S. report "Lighting for Flour Mills")	
Rolling	70
Sifting	70
Purifying	70
Packing	70
Product control	70
Cleaning screens, man lifts, aisleways and walkways, bin inspection	30
Forge shops (and welding)	50
Foundries	
Annealing (furnaces)	20
Cleaning	20
Core making (fine)	70
Core making (medium)	50
Grinding and chipping	70
Inspection (fine)	150
Inspection (medium fine)	100
Inspection (medium)	50
Moulding (medium)	70
Moulding (large)	50
Pouring	50
Sorting	20
Storage	20
Shipping and receiving	50
Cupola	20

TABLE 2 (*continued*)

	Current recommended practice, footcandles in service (on task or 30 in. above floor)
Shakeout	20
Garages, automobile and truck	
Storage, live	20
Storage, dead	5
Repair department and washing (pits or lifts)	70
Glass works	
Mix and furnace rooms, pressing and lehr, glass blowing machines	20
Grinding, cutting glass to size, silvering	50
Fine grinding polishing, beveling, etching, and decorating	70
Inspection	150
Glove manufacturing	
Pressing, knitting, sorting	
Light goods	30
Medium goods	70
Dark goods	150
Cutting, stitching, trimming, inspection	
Light goods	50
Medium goods	150
Dark goods	300[b]
Hallways, corridors, and passageways	10
Hangars, airplane	
Storage, live	30
Repair and servicing	100
Hat manufacturing	
Dyeing, stiffening, braiding, cleaning, and refining	
Light	30
Medium	70
Dark	150
Forming, sizing, pouncing, flanging, finishing, and ironing	
Light	50
Medium	70
Dark	150
Sewing	
Light	50
Medium	150
Dark	300[b]
Ice making	
Engine and compressor room	20
Inspection	
Rough	50
Medium	100
Fine	200
Extra fine	500[d]
Iron and Steel Processing	
Billet, blooming, sheet bar, skelp and slabbing mills	20
Boiler room, power house, foundry, and furnace rooms	20
Hot sheet and hot strip mills	20
Cold strip, pipe, rail, rod, tube, universal plate and wire drawing	30
Merchant and sheared plate mills	50
Tin plate mills	
Hot strip rolling and tinning machine department	20
Cold strip rolling	30
Inspection	
Black plate, bloom and billet chipping	50
Tin plate and other bright surfaces	70
Machine shops and maintenance department repair shops	
Rough bench and machine work	50
Medium bench and machine work	100
Fine work — buffing, polishing, etc.	200
Extra fine work	500
Forging	50
Laboratories (chemical and physical)	100
Carpenter and pattern shop (*see* Woodworking)	
Storage	10
Jewelry and watch manufacturing	500[d]
Laundries	
Washing	30
Flatwork ironing, weighing, listing and marking	30

(*continued*)

TABLE 2 (*continued*)

	Current recommended practice, foot candles in service (on task or 30 in. above floor)
Machine and press finishing, sorting	50
Fine hand ironing	100
Leather manufacturing	
Vats	10
Cleaning, tanning, and stretching	20
Cutting, fleshing, and stuffing	30
Finishing and scarfing	50
Leather working	
Pressing, winding, and glazing	
Light	50
Medium	70
Dark	150
Grading, matching, cutting, scarfing, sewing	
Light	50
Medium	150
Dark	300[b]
Locker rooms	20
Machine shops	
Rough bench and machine work	50
Medium bench and machine work, ordinary automatic machines, rough grinding, medium buffing and polishing	150
Extra fine bench and machine work, grinding—fine work	500[b]
Meat packing	
Slaughtering	20
Cleaning, cutting, cooking, grinding, canning, packing	70
Offices	
Difficult seeing tasks	100
Auditing and accounting	
Business machine operation	
Transcribing and tabulation	
Bookkeeping	
Drafting	
Designing	
Ordinary seeing tasks	70
General office work (except for work coming under "Difficult seeing tasks" above)	
Private office work	
General correspondence	
Conference rooms	
Active file rooms	
Mail rooms	
Casual seeing tasks	20
Inactive file rooms	
Reception rooms	
Stairways	
Washrooms, and other service areas	
Simple seeing tasks	10
Hallways and corridors	
Passageways	
Packing and boxing	30
Paint manufacturing	
General	50
Comparing mix with standard	200[d]
Paint shops	
Dipping, simple spraying, firing	30
Rubbing, ordinary hand painting and finishing art, stencil and special spraying	50
Fine hand painting and finishing	100
Extra fine hand painting and finishing (automobile bodies, piano cases, etc.)	300[c]
Paper box manufacturing	
Light	30
Dark	70
Storage	10
Paper manufacturing	
Beaters, grinding, calendering	20
Finishing, cutting, trimming paper-making machines	50
Hand counting, wet end of paper machine	70
Paper machine reel, paper inspection and laboratories	70
Rewinder	150
Storage	10
Plating	30
Polishing and burnishing	50
Power plants, engine room boilers	
Boilers, coal and ash handling, storage battery rooms	20

TABLE 2 (*continued*)

Auxiliary equipment, oil switches, and transformers	30
Engines, generators, blowers, compressors	30
Switchboards	70[e]
Printing industries	
Type foundries	
Matrix making, dressing type	150
Hand casting	50
Machine casting	30
Printing plants	
Color inspection	200[b]
Machine composition	200[b]
Presses	70
Imposing stones	150[c]
Proof reading	150
Electrotyping	
Molding, finishing, leveling molds, routing, trimming	150
Blocking, tinning	50
Electroplating, washing, backing	30
Photoengraving	
Etching, staging	30
Blocking	50
Routing, finishing, proofing	70
Tint laying	150
Masking	150
Receiving and shipping	50
Rubber tire and tube manufacturing	
Stock preparation	
Bradbury	30
Plasticating	30
Milling	30
Calendering	50
Fabric preparation	
Stock cutting	50
Bead building	50
Tube tubing machines	30
Tread tubing machines	30
Tire building	
Solid tire	30
Pneumatic tire	70
Curing department	
Tube curing	70
Casing curing	70
Final inspection	
Tube	100
Casing	150
Wrapping	30
Warehouse	10
Rubber goods—mechanical	
Stock preparation	
Plasticating	30
Milling	30
Calendering	50
Bradbury	30
Fabric preparation	
Stock cutting	50
Hose looms	50
Molded products and curing	70
Extruded products	50
Inspection	150
Boxing	30
Warehouse	10
Sheet metal works	
Miscellaneous machines, ordinary bench work	50
Presses, shears, stamps, spinning, medium bench work	50
Punches	50
Tin plate inspection	70
Scribing	150[c]
Shipyards	
General	5
Ways and fabrication areas	20
Shoe manufacturing (leather)	
Cutting and stitching	
Cutting tables	50
Marking, buttonholing, skiving, sorting, vamping and counting	
Light materials	50
Dark materials	150
Stitching	
Light materials	100
Dark materials	300[b]
Making and finishing	
Stitchers, nailers, sole layers, welt beaters and scarfers, trimmers, welters, lasters, edge setters, sluggers, randers, wheelers, treers, cleaning, spraying, buffing, polishing, embossing	
Light materials	50
Dark materials	150
Storage, packing, and shipping	30
Shoe manufacturing (rubber)	
Washing, coating, mill run compounding	30
Varnishing, vulcanizing, calendering, upper and sole cutting	50
Sole rolling, lining, making and finishing processes	100

(*continued*)

TABLE 2 (*continued*)

Soap manufacturing	
Kettle houses, cutting, soap chip and powder	30
Stamping, wrapping and packing, filling and packing soap powder	50
Stairways, reception rooms, washrooms, and other service areas	20
Stone crushing and screening	
Belt conveyor tubes, main line shafting spaces, chute rooms inside of bins	10
Primary breaker room, auxiliary breakers under bins	10
Screens	20
Storage battery manufacturing	
Molding of grids	50
Storage rooms	
Inactive	10
Active	
Rough bulky	20
Medium	30
Fine	50
Structural steel fabrication	30
Sugar refining	
Grading	50
Color inspection	150
Switchboards (see control rooms)	
Testing	
Rough	30
Fine	50
Extra fine instruments, scales, etc.	200
Textile mills (cotton):	
Opening, mixing, picking	30
Carding and drawing	30
Slubbing, roving, spinning and spooling	50
Beaming and slashing on comb	
Grey goods	50
Denims	150
Inspection	
Grey goods (hand turning)	70
Denims (rapidly moving)	300^d
Automatic tying-in	150
Drawing-in by hand	300^d
Weaving	70
Textile mills (silk and rayon)	
Manufacturing	
Soaking, fugitive tinting, and conditioning or setting of twist	30
Winding, twisting, rewinding, and coning, quilling, slashing	
Light thread	50
Dark thread	100
Warping (silk or cotton system) on creel, on running ends, on reel, on beam, on warp at beaming	70
Drawing-in	
On heddles	150
On reed	150
Weaving	
On heddles and reeds	50
On warp back of harness	50
On woven cloth	70
Textile mills (woolen and worsted)	
Opening	30
Grading	150^b
Blending	30
Picking	30
Carding (add an internal unit)	70
Combing	70
Recombing	70
Gilling	70
Drawing (white)	50
Drawing (colored)	100
Spinning (frame) (white)	50
Spinning (frame) (colored)	100
Spinning (mule) (white)	50
Spinning (mule) (colored)	100
Twisting (white)	50
Winding (white)	50
Winding (colored)	100
Warping (white)	50
Warping (white) (at reed)	100^b
Warping (colored)	100
Warping (colored) (at reed)	150^b
Weaving (white)	70
Weaving (colored)	200
Grey goods room	
Burling	150^b
Sewing	300^b
Folding	70
Wet finishing	
Fulling	50
Scouring	50
Crabbing	50
Drying.	50
Dyeing	150^b
Dry finishing	
Napping	70
Shearing	150^b
Conditioning	70
Pressing	70
Inspecting (perching)	500
Folding	70
Tobacco products	
Drying, stripping, general	30

TABLE 2 (*continued*)

Grading and sorting	150
Toilets and wash rooms	20
Upholstering—automobile, coach furniture	70
Warehouse	20
Washrooms	20
Welding	
General illumination	50
Supplementary illumination	2000
Woodworking	
Rough sawing and bench work.	50
Sizing, planing, rough sanding, medium machine and bench work, glueing, veneering, cooperage	100
Fine bench and machine work, fine sanding and finishing	200

[a] The footcandle recommendations may change as a result of a number of studies now under way. It is desirable to consult specific study reports at the time of design.

[b] Obtained with a combination of general lighting plus specialized supplementary lighting.

[c] Special lighting such that (1) the luminous area shall be large enough to cover the surface which is being inspected and (2) the brightness be within the limits necessary to obtain comfortable contrast conditions. This involves the use of sources of large area and relatively low brightness in which the source brightness is the principal factor rather than the footcandles produced at a given point.

[d] These seeing tasks generally involve the discrimination of fine detail for long periods of time and under conditions of poor contrast. To provide the required illumination, a combination of the general lighting indicated plus specialized supplementary lighting is necessary. The design and installation of the combination system must not only provide a sufficient amount of light, but also the proper direction of light, diffusion, and eye protection. As far as possible it should eliminate direct and reflected glare as well as objectionable shadows.

[e] For all power plants.

trial areas over the past 40 years. Present-day recommendations for various industrial operations are given in Table 2. Quality lighting has resulted in many lighting benefits to the employee and the employer alike.[49]

One of these is the safety of employees in industry. The correlation between accident prevention and better lighting is well established. People closely connected with lighting for industry know that under good lighting conditions the worker can see faster and does not tire as easily as under poor lighting conditions. In a survey by an industrial firm[50] in their erection shop, it was found that accidents were cut 32 per cent when lighting was increased from 5 to 20 footcandles (Figures 13 and 14). Then, after the walls were painted with a fairly high-reflectance paint (Figure 15), the accident rate decreased another $16^{1}/_{2}$ per cent (Figure (16); this painting served to increase illumination to about 25 footcandles and increased seeing ability on vertical surfaces as well as creating a more comfortable environment in which to work.

Another example of a reduction in accident rate due to better lighting conditions is found in a machine tool company[51] (Figures 17 and 18). Installation of fluorescent luminaires with an upward component of light provided better lighting and more comfortable seeing conditions. The illumination level was raised from 3 to 40 footcandles. Machines were painted a 30 per cent gray reflectance to reduce

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[49] 25 industrial lighting solutions, *Bulletin* **LS-163,** Lamp Division, General Electric Co., January, 1955.

[50] Allis-Chalmers Manufacturing Co., Erection Shop, Milwaukee, Wis.

[51] Morris Machine Tool Co., Second Floor Machinery Area, Cincinnati, Ohio.

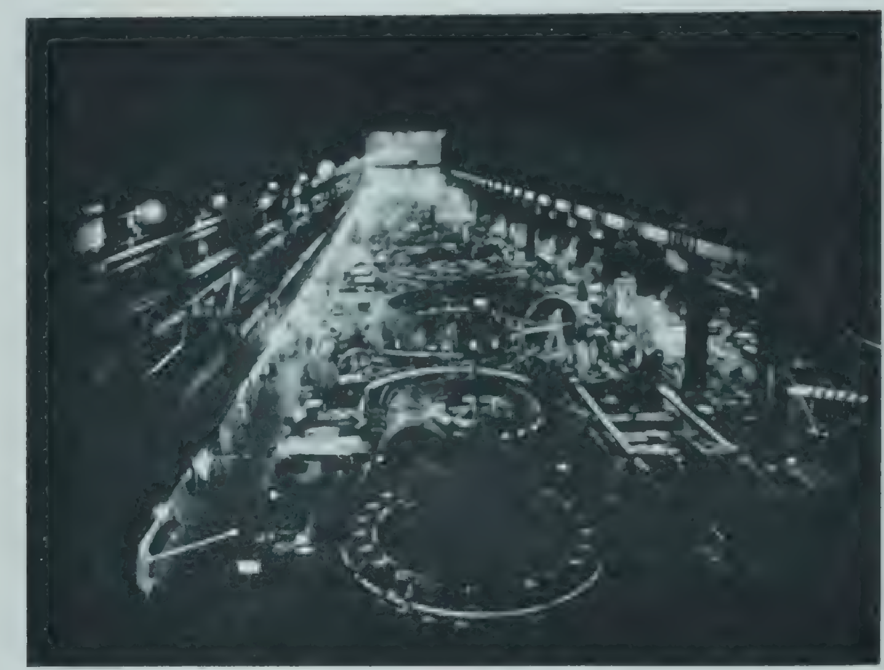

Figure 13. A view of an industrial firm's erection shop before relighting. Management noticed that the accident rate in this area was high. Employees were working in shadows.

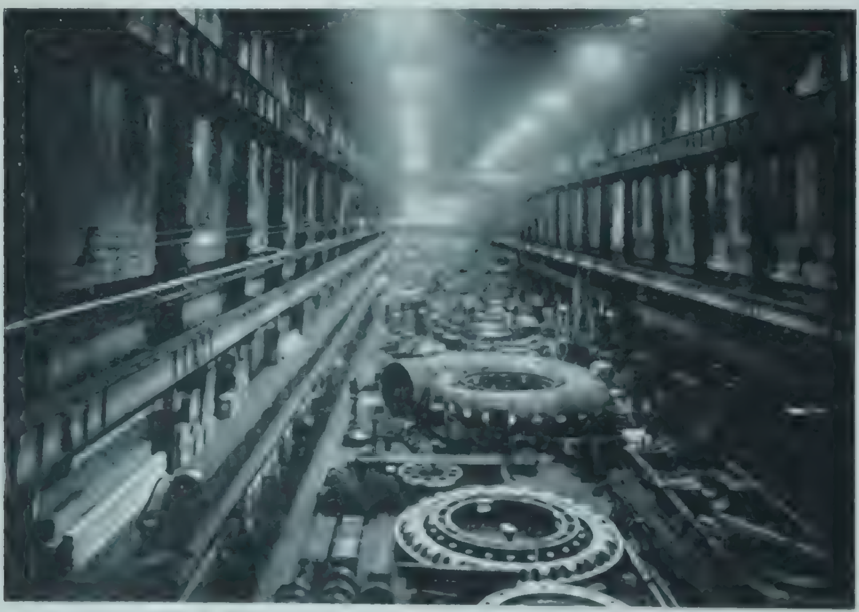

Figure 14. The same shop as in Figure 13 after relighting to about 20 footcandles, using 3000-watt mercury lamps plus a few incandescent lamps to provide light in case of a power interruption.

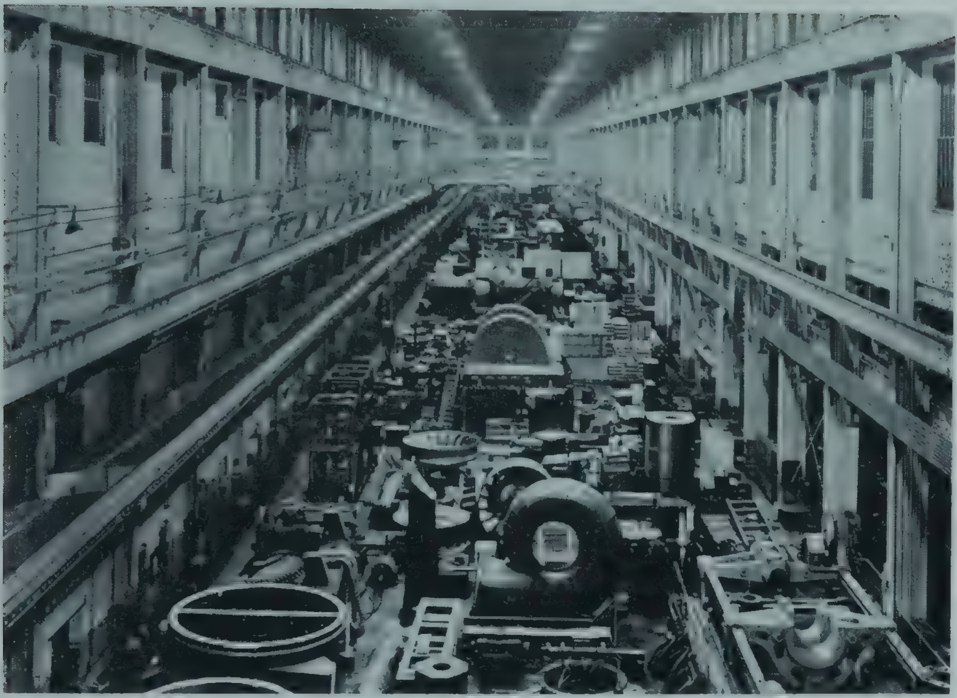

Figure 15. The same shop as in Figures 13 and 14 after painting. In addition to raising the footcandle level, the paint created a more pleasing atmosphere in which to work, minimized shadows, and increased illumination on vertical work surfaces.

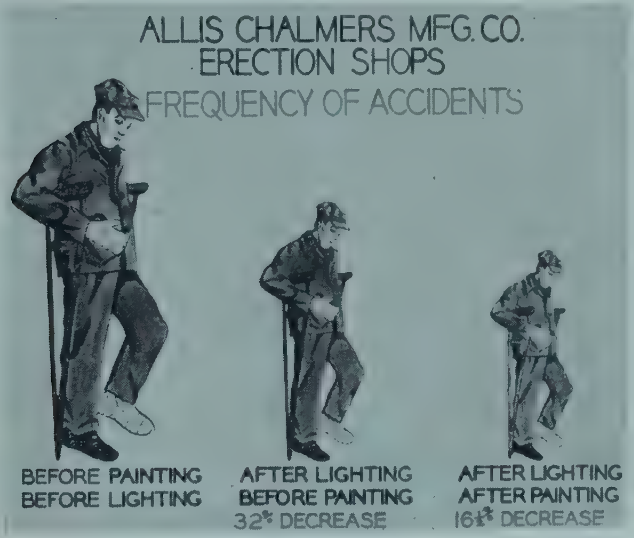

Figure 16. Benefits derived from relighting and painting the erection shop. Accident rate reduced 32 per cent after relighting and decreased $16^1/_2$ per cent further after painting.

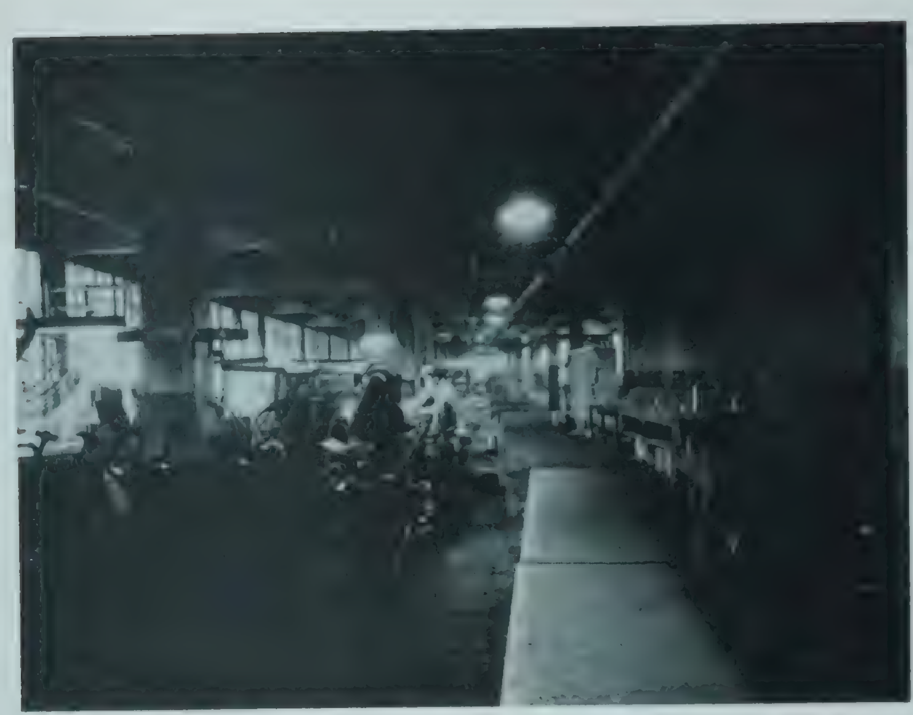

Figure 17. A view of a tool company machinery area before relighting and painting. Incandescent lamps in industrial reflectors provided an average illumination of 3 footcandles.

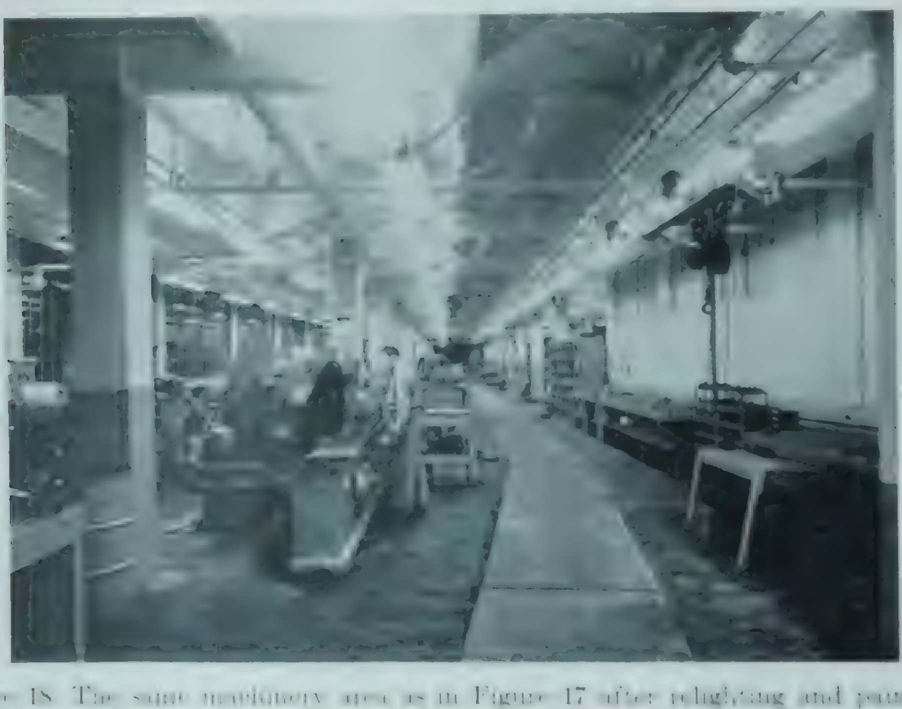

Figure 18. The same machinery area as in Figure 17 after relighting and painting. Two-lamp industrial fluorescent fixtures with 10 per cent upward light, using cool white fluorescent lamps. Average illumination is 40 footcandles.

brightness contrasts. Under these new conditions the accident rate has been cut 35 to 50 per cent.

Other benefits of good lighting include increased production rate and reduced spoilage. A textile mill[52] has kept statistics on their textile products throughout an extended re-lighting program. Their production rate and mending costs are correlated with illumination in Table 3 and Figure 19. Figure 20 shows a typical weave room of this firm. Note the high-quality lighting system as well as the above-average (70 footcandles) quantity. Later installations in the chain of mills use over 100 footcandles.

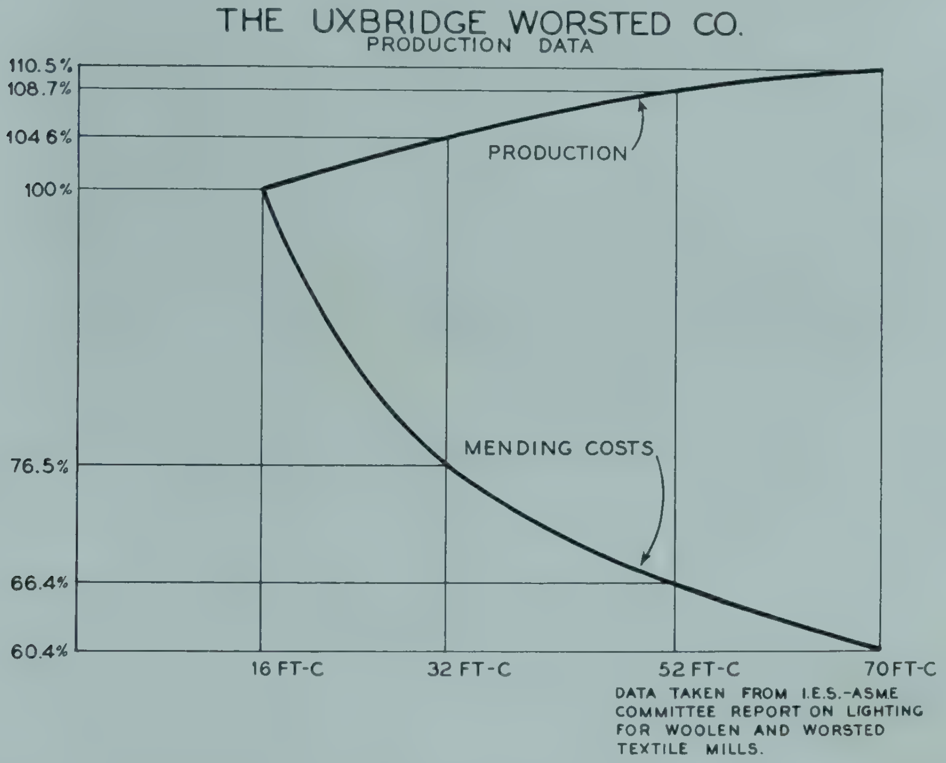

Figure 19. The increase in production and decrease in mending costs under increasing illumination levels in a textile mill. Although increased production is important, the company feels that the mending-cost curve is even more important since it reflects the quality of their product.

TABLE 3

Illumination (footcandles)	16	32	52	70
Production rate (per cent)	100	104.6	108.7	110.5
Mending costs (per cent)	100	76.5	66.4	60.4

Benefits of good seeing conditions also include higher morale of the employees, less eyestrain, and better housekeeping. These contribute to safer working condi-

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[52] The Bachman Uxbridge Worsted Corp., Macon Textile Plant, Macon, Ga.

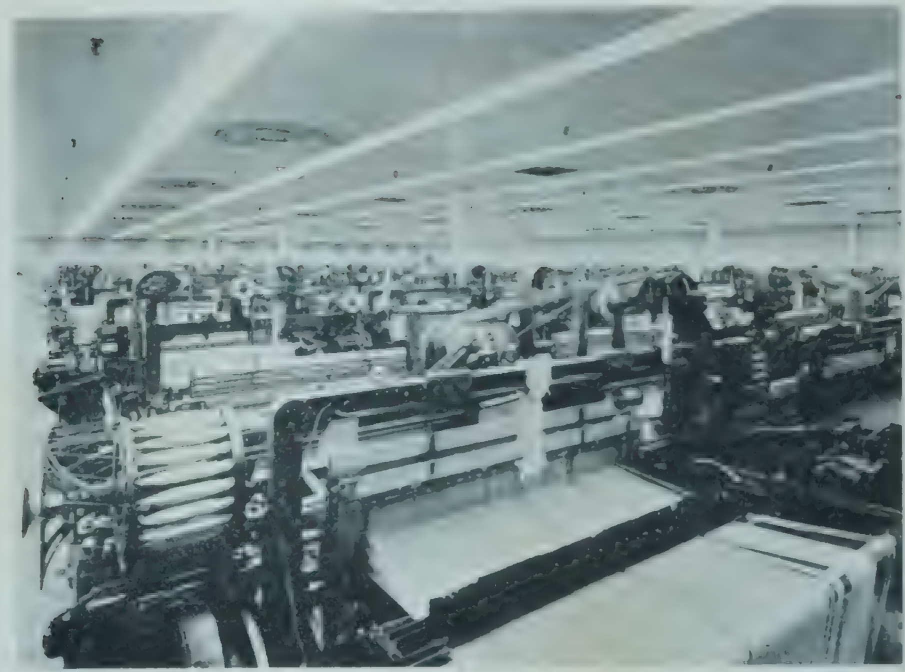

Figure 20. A typical weave room using recessed troffers with an acoustical tile ceiling. Ceiling is brightened by light reflected onto it from light-colored fabrics and light floors.

tions and higher production, which are reflected in more efficient performance and a better employee-employer relationship.

IX. General Lighting

For general lighting of industrial areas[53,54] where lamps are mounted less than 20 feet from the floor, fluorescent lamps are usually preferred because of their efficiency and low brightness. Thus, they lend themselves well to higher levels of quality illumination (Figure 21). The luminaire used with these lamps should be chosen carefully to provide good shielding of the lamps and a substantial upward component of light (Figure 22). Room surfaces should be light in color to reflect light to the work surface efficiently and to brighten the surrounds. All these considerations have the effect of reducing objectionable brightness contrasts in the room interior.

For high mounting conditions filament and mercury light sources are most often used. In general, the higher the mounting, the larger the lamp used (Figure 23). With higher-output lamps maintenance costs are reduced, since fewer lamps are required, but their higher brightness necessitates mounting them at a greater distance from the workers' eyes to reduce glare. Filament lamps have a lower initial cost and better color quality than the mercury type. On the other hand,

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[53] Planned lighting for industry, *Bulletin* **LD-4**, Lamp Division, General Electric Co., November, 1951.

[54] L. V. James, Lighting for seeing in industry, *Plant Engineering*, 73, January, 1953.

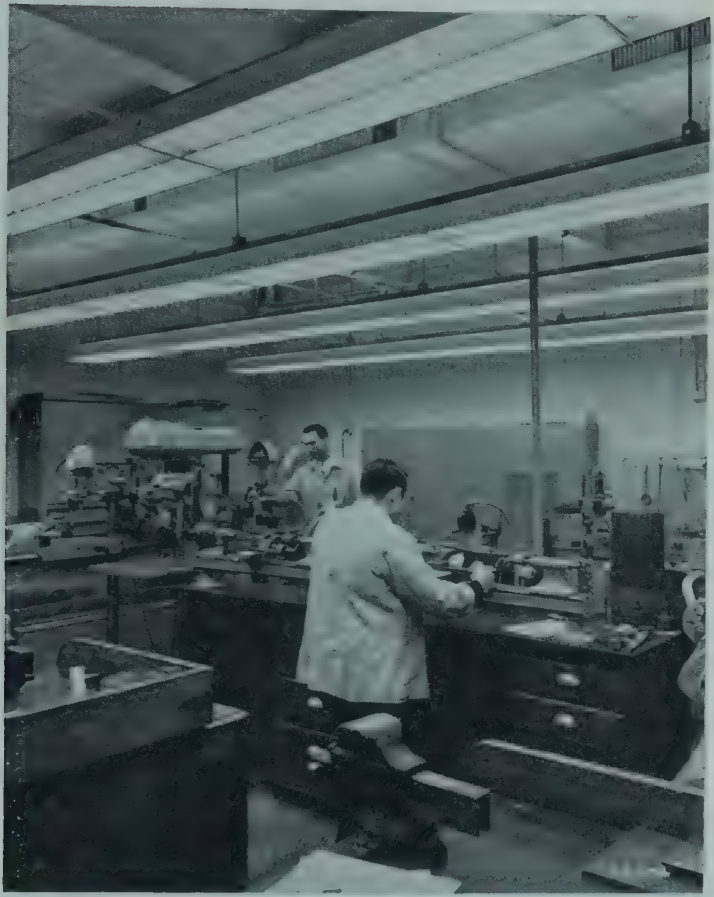

Figure 21. Quality lighting in a machine shop. Illumination level of 175 footcandles, which is needed for the very fine machine work done. Well-shielded fixtures with an upward light component were used.

mercury lamps are more efficient and have a longer life. Color-improved mercury lamps, although they do not produce as good color rendition as filament or fluorescent lamps, have gained wide popularity in the last few years. They should, however, be supplemented with filament lamps for safety in case of power interruption.

Where sources are dependent on a reflector to control and redirect their light, lamps and reflectors must be cleaned periodically to obtain light efficiently. Both mercury and filament sources are available in reflector lamps that have the light-controlling surface enclosed within the glass bulb (Figure 24). The total annual cost of a reflector lamp installation is often less than external-reflector systems because of reduced cleaning costs.[55] They are especially suited for heavy industry where there are large amounts of dirt and dust in the air.

Fluorescent lighting is also used for high mounting applications where good maintenance is feasible (Figure 25). The better quality of lighting inherent in a

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[55] E. A. Linsday, Let's reduce the cost of lighting, *Elec. Eng.*, **73**, 632 (1954).

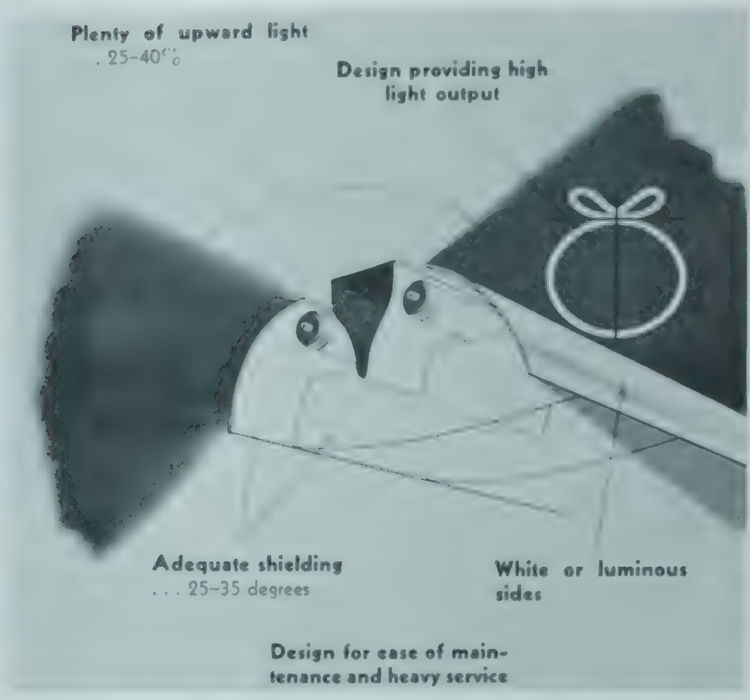

Figure 22. The important factors to be considered in designing or choosing an industrial fluorescent lighting fixture to provide quality illumination.

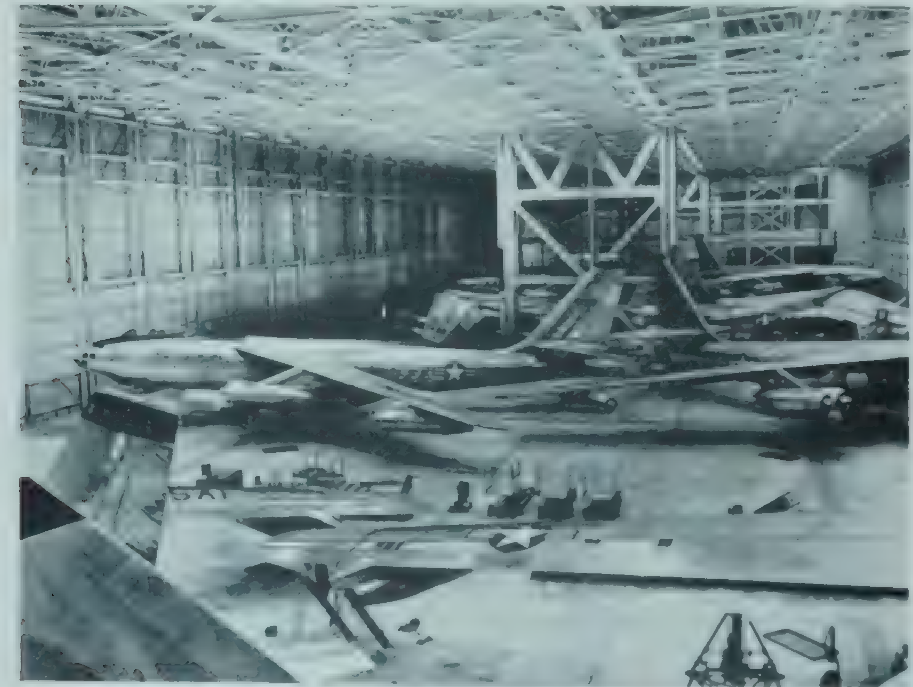

Figure 23. An airplane plant showing the application of a combined mercury-filament lighting system in a high mounting area. Mercury lamps of the 1000-watt variety provide the major portion of the illumination, while the 1000-watt filament lamps improve the color rendition.

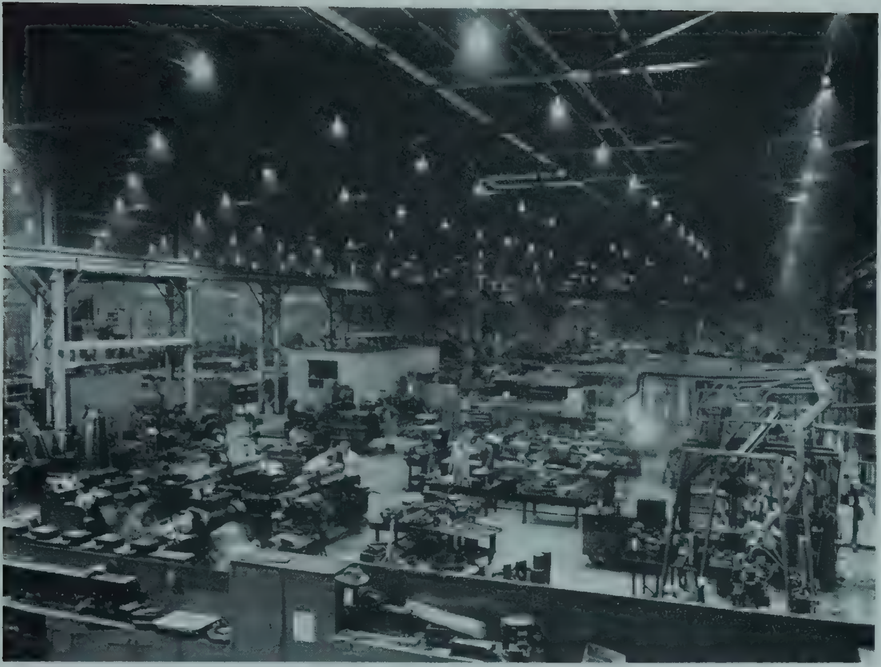

Figure 24. An installation of 750-watt reflector-type filament lamps in an area where dirt and dust would make external reflectors prohibitively costly to maintain adequately. The illumination is 35 footcandles from these lamps, which are mounted 30 feet above the floor on 15-foot centers.

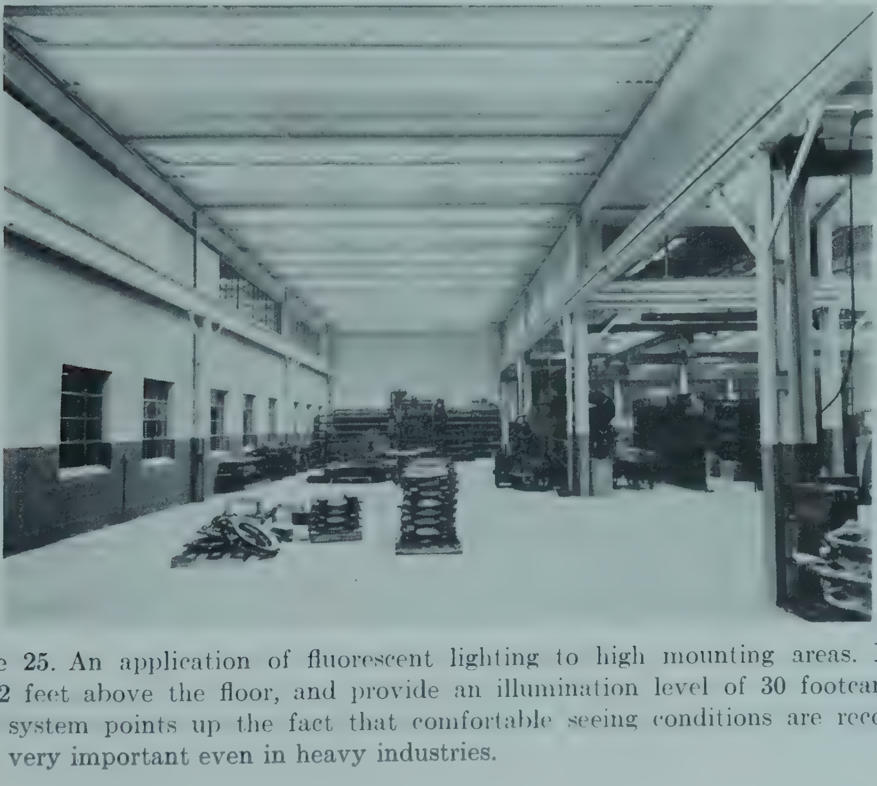

Figure 25. An application of fluorescent lighting to high mounting areas. Lamps are mounted 22 feet above the floor, and provide an illumination level of 30 footcandles. This fluorescent system points up the fact that comfortable seeing conditions are recognized by industry as very important even in heavy industries.

well-designed fluorescent system may be obtained at little additional cost,[56] and in many cases the total cost per footcandle of illumination is lower than with a filament system.

A. MAINTENANCE

A good lighting system requires a good maintenance program, which includes periodic cleaning[57] of lamps and fixtures, repainting of room surfaces, and replacing burned-out lamps.

Dirt and dust accumulation on lamps and fixtures[58] can reduce light output by as much as 50 per cent (Figure 26). Not only is the generated light that is not being utilized expensive, but also the loss in illumination may result in lower production and an increased accident rate. For servicing high mounting installations in large areas it is sometimes economical to provide built-in catwalks or movable platforms suspended on a cable (Figure 27) or the crane rails. For fixtures that are mounted lower, scaffolds, movable platforms, or fork trucks are the usual methods employed. Whenever possible, all cleaning equipment, wash-tanks, and replacement lamps should be within easy reach of the maintenance man to conserve time and cost of cleaning and relamping. In the average industrial

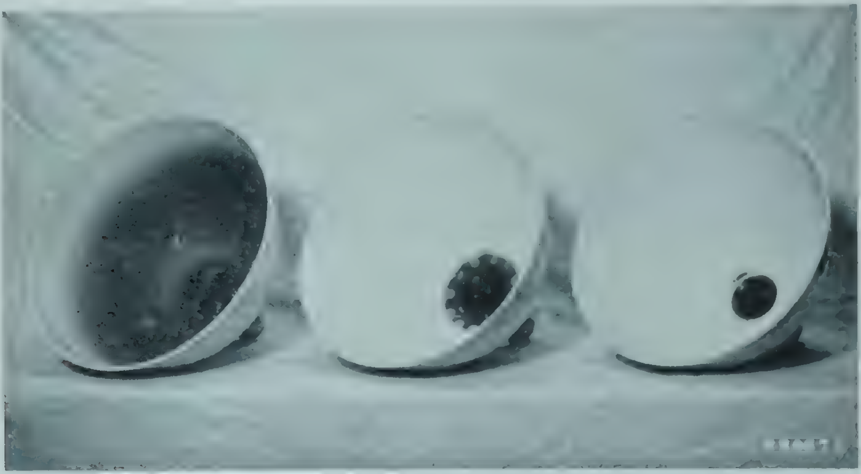

Figure 26. The effect of ventilation on dirt accumulation on reflector surfaces. Dust and dirt settle onto the reflector (left) when no ventilating holes or slots are present. Holes near the top of the reflector (center) provide an exit for the dust laden air, warmed by the lamp, to pass through. Portion of reflector below the holes is thus kept cleaner. Holes placed in the husk (right) provide this same chimney effect keeping the entire reflector surface cleaner.

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[56] A. C. Barr and C. L. Amick, Fundamentals of lighting cost analysis. *Illum. Eng.* **47**, 260 (1952).

[57] Lighting maintenance—cleaning. *Bulletin* **LS-166**, Lamp Division, General Electric Co., December, 1954.

[58] C. E. Egeler and R. F. VandenBoom, Maintenance of industrial lighting. *Illum. Eng.* **46**, 522 (1951).

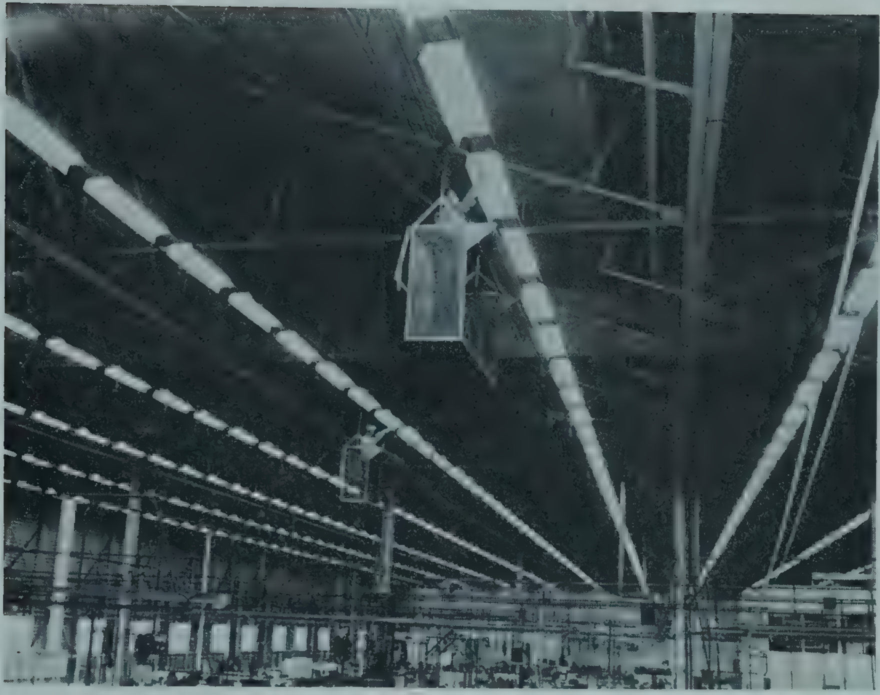

Figure 27. Maintenance of fluorescent fixtures at high mounting is simplified by a system of maintenance cages suspended from cables. Cage, including maintenance man and cleaning equipment, can easily be pulled forward or back by the operator.

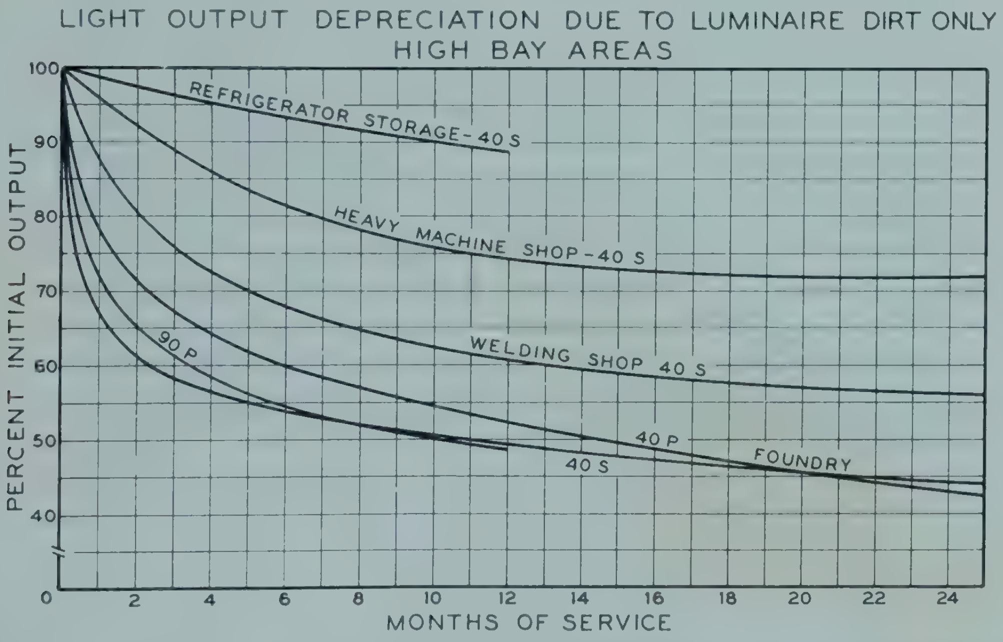

Figure 28. Light-output depreciation due to luminaire dirt only, in heavy industry. *P* and *S* represent porcelain enamel and synthetic enamel fixtures, respectively. Wattage of fluorescent lamps used is indicated by the numbers.

area cleaning at least twice per year is recommended,[59] but this varies widely depending on the rate of dirt accumulation and the type of lighting system installed. Figure 28 shows some typical conditions.

Relamping is done either on an individual replacement basis or on a group replacement plan.[55,60] With the consistent lamp life characteristic of present-day sources, the group replacement plan is usually the more economical. Lamps are replaced at 70 to 80 per cent rated life, and the few burnouts between replacement schedules can be replaced individually with the best of the operable lamps from the previous group. Group relamping may be done during a cleaning operation to further cut costs. Under the group relamping plan the small additional cost of lamps is offset by the reduction in labor cost of doing the job on a mass-production basis.

X. Supplementary Lighting

In many applications the general lighting system alone is not sufficient, and some kind of supplementary lighting[61-63] is necessary (Figure 29). It must be kept in mind that supplementary lighting is just what the word implies—lighting that supplements the general lighting system. A good general lighting system is still necessary to provide an over-all comfortable seeing environment. Where the object or task is small in size or has little contrast with its immediate background, an additional quantity of light supplied by a supplementary system increases the worker's seeing ability. For these tasks a well-shielded source directed at the work is employed.

Directional lighting is often used for detecting scratches, pits, and surface flaws on nonspecular materials (Figure 30). For this purpose a beam of light provided by narrow-beam reflectors, lenses, or spot lamps is directed at a grazing angle across the surface of the material being inspected. Defects will show up as highlights or shadows. This method may sometimes be used also on specular materials. The surface to be inspected appears dark to the operator, except for imperfections, which appear bright because they reflect light. One must be particularly careful to control the directional beam of light so that it is shielded from the operator's eyes and from other persons.

A third technique employs a diffuse light source, generally large in area and

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[59] C. E. Egeler and R. F. VandenBoom, Maintenance of industrial lighting—Part II. *Illum. Eng.*, **48**, 631 (1953).

[60] Lighting maintenance—group relamping. *Bulletin* **LS-155**, Lamp Division, General Electric Co., December, 1953.

[61] Recommended practice for supplementary lighting (Prepared by the Subcommittee on Supplementary Lighting of the Committee on Lighting Study Projects in Industry of the Illuminating Engineering Society), *Illum. Eng.*, **47**, 623 (1952).

[62] C. M. Cutler and E. A. Linsday, Supplementary lighting. *Magazine of Light*, **20**, 10 (November, 1951).

[63] E. A. Linsday, Specialized lighting for inspection and control. *Ind. Quality Control*, **11**, 357 (1954).

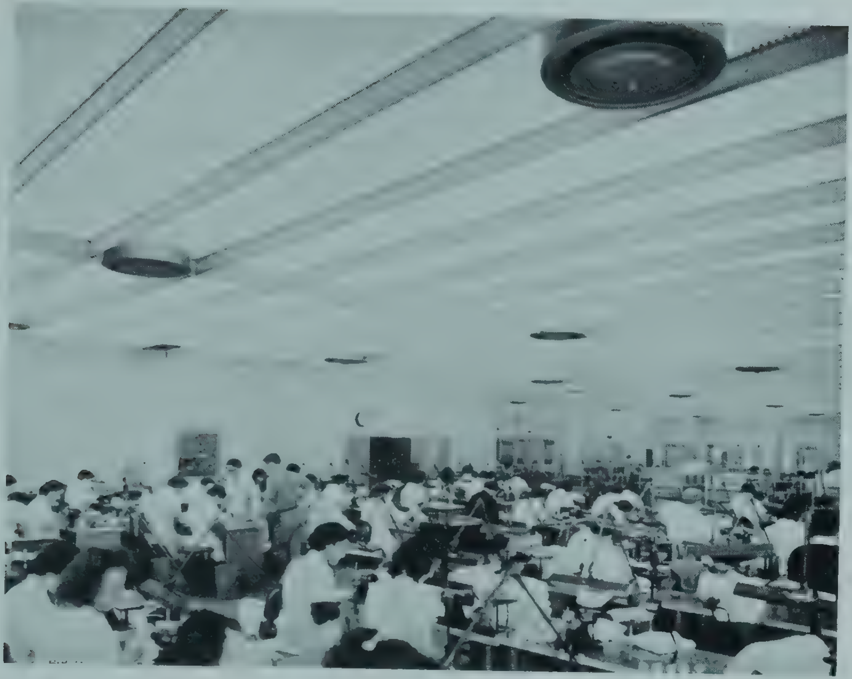

Figure 29. Supplementary lighting provided by adjustable units near the task, which contain two 15-watt fluorescent lamps. A good general lighting system is necessary to provide balanced brightness and a comfortable surround.

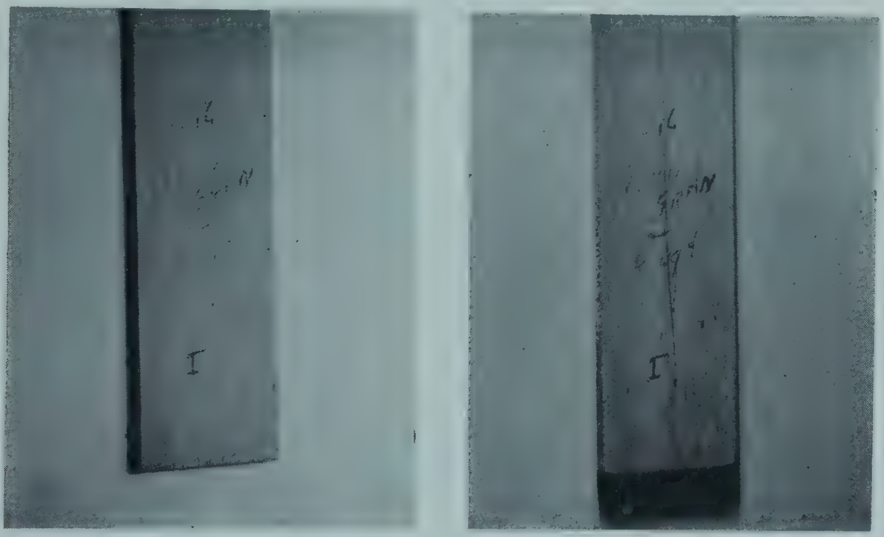

Figure 30. Rough surface on an unsanded Venetian blind slat (right) is easily detected with a beam of light directed at a grazing angle across the surface. Under diffused light (left), surface roughness is not as apparent.

uniform in brightness, for illuminating the material to be inspected (Figures 31 and 32). It may also be used for transilluminating materials such as photographic negatives, bottles, and fabrics for inspection purposes (Figure 33). Diffused sources with a pattern of lines painted on the translucent panel are used to detect

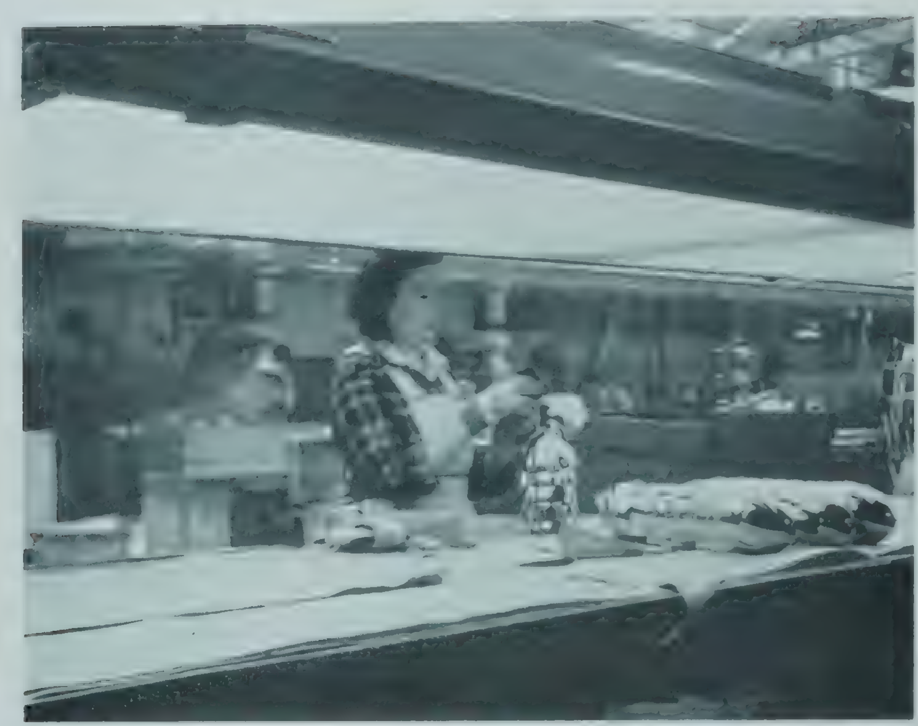

Figure 31. Inspection for flaws and even coverage of chrome-plated pieces of metal. Low-brightness, large-area light source was made from two fixtures placed side by side, the bottom covered over with tracing vellum to diffuse the light.

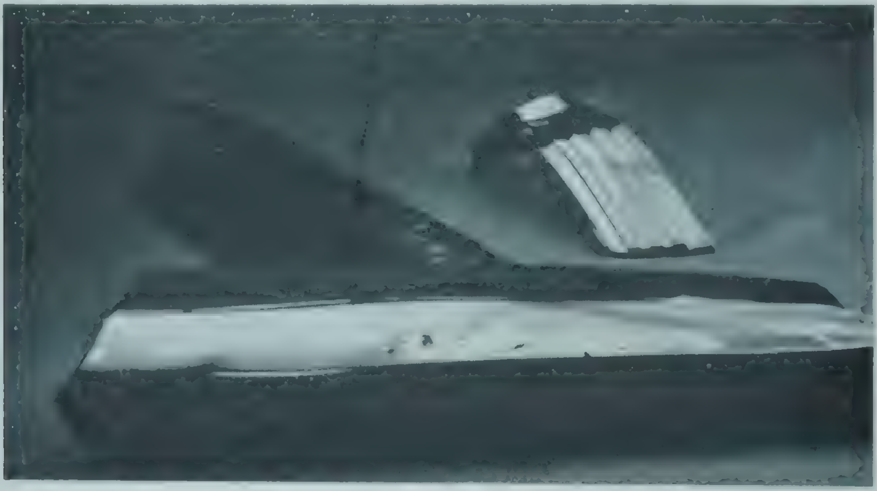

Figure 32. Close-up of pieces of specular metal. Surface flaws and uneven coverage of chrome plating show up as dark spots and smears.

surface flaws in specular materials by reflection of the pattern (Figure 34). Irregularities in the reflected lines indicate these surface defects.

Specialized techniques, such as black light (Figure 35), polarized light (Figures 36 and 37), magnification (Figure 38), magnification and projection (Figure 39), and colored light (Figure 40), are also useful for particular applica-

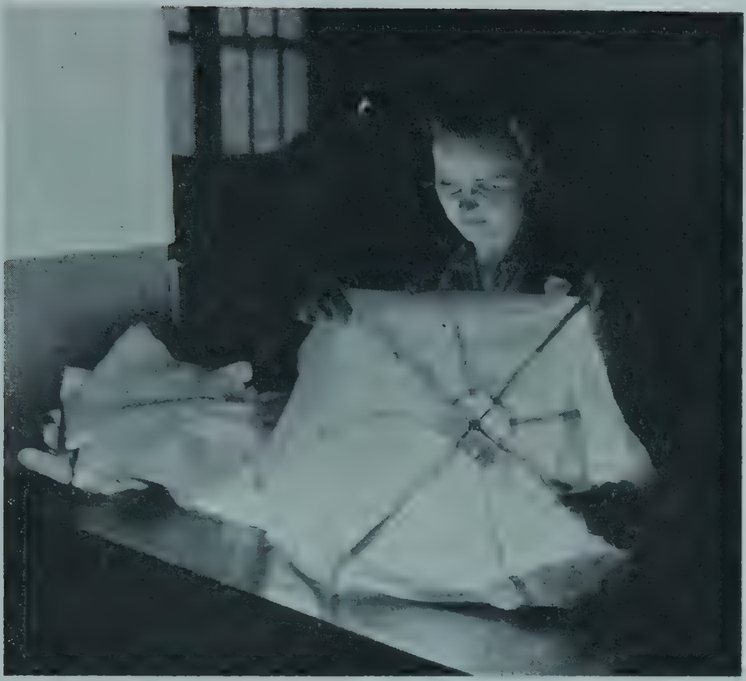

Figure 33. Seams in any light-weight fabric, such as a parachute, are more readily inspected when transilluminated by a unit using either fluorescent or filament lamps behind the diffusing material. Inside of box is finished white to more efficiently utilize and diffuse the light.

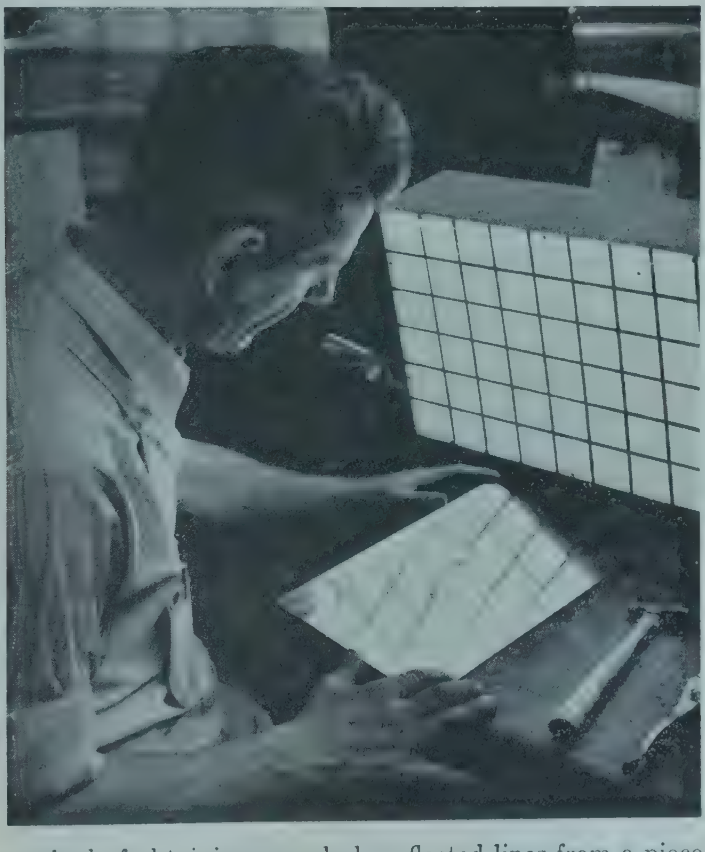

Figure 34. A method of obtaining specularly reflected lines from a piece of specular metal. Unit contains three 15-watt fluorescent lamps behind a diffusing panel with black painted criss-cross lines. Irregularities in reflected lines show up dings and dents in the material.

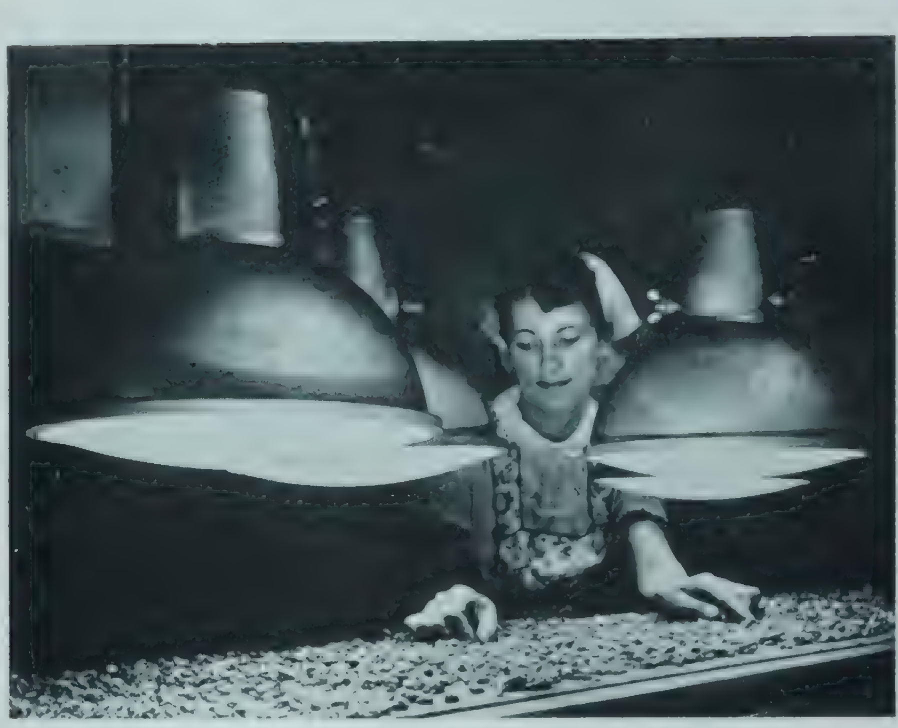

Figure 35. Inspection of pecans. Black light makes wormy pecans glow, whereas good pecans ar unaffected, thus making it a simple task to sort out and reject the wormy ones.

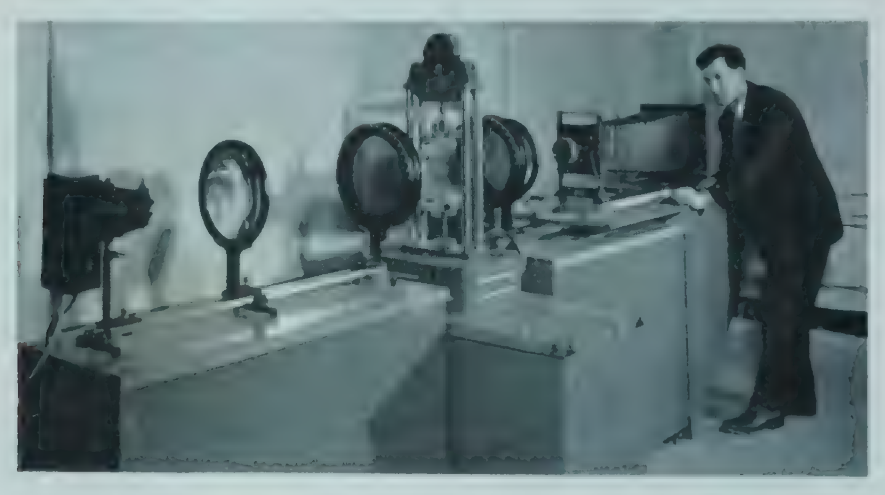

Figure 36. An application of polarized light for inspecting strains in plastic models of metal airplane parts when under tension or compression. Light source is a 250-watt mercury lamp; plastic model is placed in the compression device located between two polaroid screens.

tions. Black light is used in metal industries for the inspection of cracks in metal parts. Polarized light finds its application in detecting stresses and strains in transparent parts and plastic models of metal parts. Where very small objects are being inspected, magnification and projection facilitate the process. Colored light is an ideal solution for inspecting color proofs in the printing industry.[64] A

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[64] Colored light for color printing. *Bulletin* **LS-122**, Lamp Division, General Electric Co May, 1949.

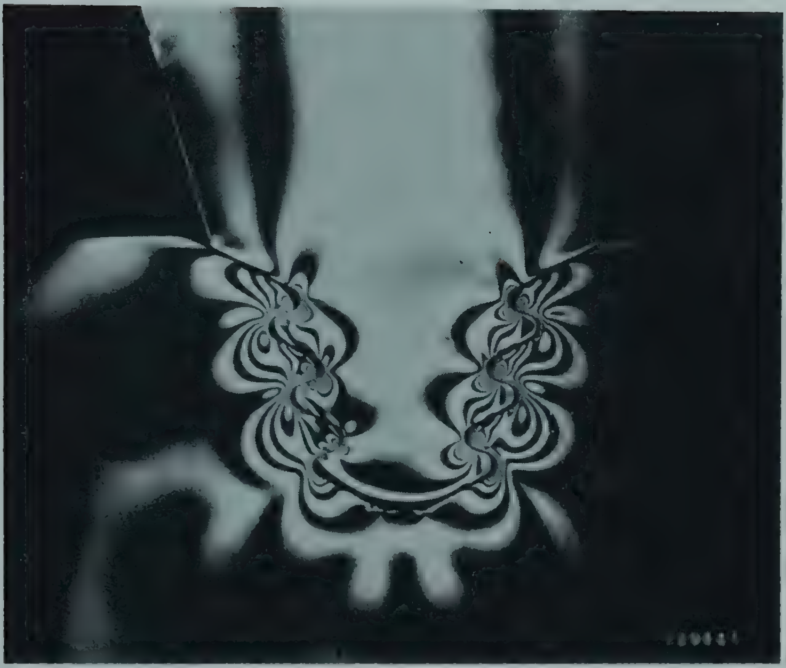

Figure 37. Close-up view of the plastic model in Figure 36, as seen on a ground-glass screen in the back of the camera. The amount of stress or strain is determined by the closeness of spacing of dark and light areas around the strain points.

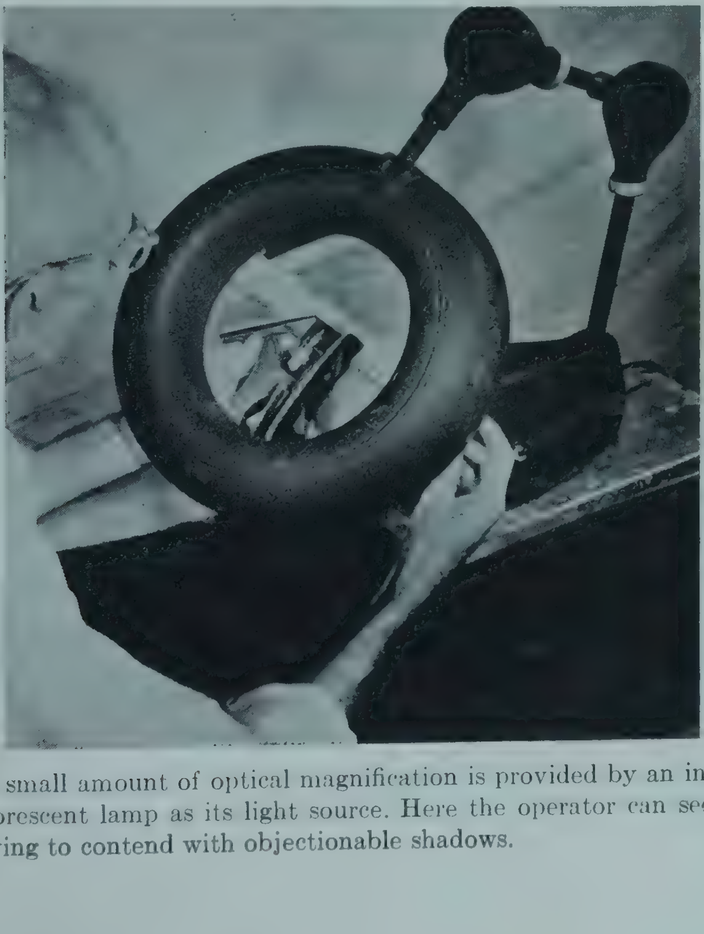

Figure 38. A small amount of optical magnification is provided by an inspection unit that uses a circline fluorescent lamp as its light source. Here the operator can see fine detail much easier without having to contend with objectionable shadows.

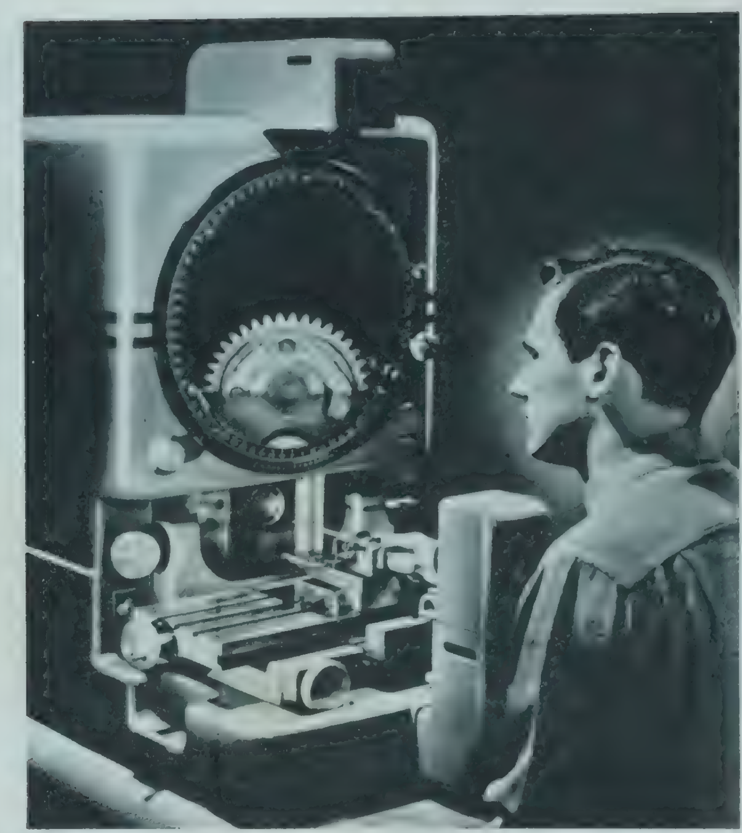

Figure 39. An example of a large amount of magnification coupled with projection onto a screen. Slight defects can be easily detected.

Figure 40. Colored light used for inspecting color proofs in the printing industry. Lig of a color complementary to the printing ink makes the ink appear dark grey against the lig background; for example, using blue light on yellow proofs.

colored proof viewed under light of a complementary color has a greater contrast with its background.

These illustrations serve to give some idea of the many places where supplementary lighting for inspection of difficult seeing tasks helps insure easy accurate seeing. In general, the technique for a certain job is developed after careful study of the problem. The application of fundamental principles in the control, color quality, and quantity of illumination contributes a great deal to the elimination of the seeing "bottlenecks" that, in many cases, are the most troublesome features of manufacturing processes.

XI. Infrared Radiation

The actual amount of infrared radiation from sources of artificial light in typical lighting installations is far below the levels that will have harmful effects upon human beings. At worst, it produces discomfort and annoyance because of its heating effects. No significant differences in visual functions were found when most of the infrared radiation was filtered out of light from tungsten filament lamps.[65] If the general heating effects are objectionable or undesirable, fluorescent lighting can be used to provide hundreds of footcandles before such effects are noticeable on the skin.[30]

Some industrial processes involve high-energy levels of infrared radiation. Long-wave infrared radiation is readily absorbed by the surface tissues of the body. Therefore, these rays cannot inflict deep injuries. Overexposure produces some immediate discomfort, which generally provides adequate warning. However, the eyes may suffer from continual exposures to infrared that is below the level that causes general discomfort. There is some evidence that this may result in cataract. Eyes should be protected by suitable glasses from intense direct radiation. Fortunately, in most situations where overexposure of the eyes to radiation may occur, visible radiation also is so intense as to require protective goggles.

XII. Ultraviolet Radiation

Since ultraviolet radiation is readily absorbed in human tissue, it produces superficial injuries, chiefly to the skin and eyes. However, most lamps used for general lighting purposes emit little or no ultraviolet radiation so that in typical lighting installations there are no harmful effects.[66] On the other hand, there are certain special-purpose lamps that are designed to emit shorter-wave radiation. Some industrial processes, such as welding, also produce considerable amounts of such radiation. In these cases it is necesary to take certain precaution.

The effects of exposure to ultraviolet radiation are similar to sunburn. Since there is a measurable period of time between exposure and development of injury, deep burns may be endured without immediate discomfort. The severity of the burn depends upon the spectral distribution of energy in the ultraviolet region, the intensity, and the time of exposure. Certain wave lengths are more effective in producing discomfort and injury than others. Figure 41 illustrates the relative effectiveness of various wave lengths in producing erythema.

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[65] M. Luckiesh and F. K. Moss, Infrared radiation and visual function, *J. Opt. Soc. Amer.*, **27**, 69 (1937).

[66] Effect of fluorescent lighting on the eyes, *J. Am. Med. Assoc.*, **124**, 608 (1944).

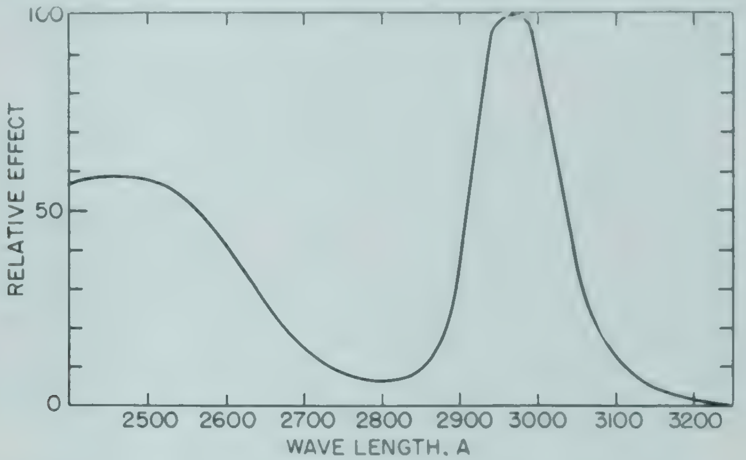

Figure 41. The selective effectiveness of various wave lengths in producing erythema.

Considerable discomfort can be produced in the eye by exposure to radiation below about 3100 Å. The absorption of this radiation by the outer layers of the eye (cornea and conjunctiva) produces conjunctivitis, which occurs 4 to 8 hours after exposure and may last several days. While conjunctivitis itself is rarely serious, great care should be taken to avoid secondary infection.

Protective glasses should be worn by all personnel when they may be exposed to erythemally effective radiation. Furthermore, opaque shielding should be used around welding areas to protect other persons.

It has been suggested[67] that 0.5 microwatt per square centimeter be the permissible amount of ultraviolet for a 7-hour continuous exposure or 0.1 microwatt per square centimeter for 24 hours.

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[67] Council on Physical Therapy, *J. Am. Med. Assoc.*, **122,** 503 (1943).

CHAPTER XXI

Heat Control in the Hot Industries

T. F. HATCH

This chapter is concerned with the protection of workers in the so-called hot industries where heat exposures are increased substantially above the normal levels fixed by the local climate because of the extra heat added to the environment by the hot processes. Industrial heat exposures may be classified as either *hot-dry* or *warm-moist.* (*1*) In the *hot-dry* industries, such as steel mills, forge shops, and glass manufacturing plants, the thermal load on the worker is increased by the sensible heat that escapes from the process equipment into the surrounding work space. The major component is radiant heat from the surfaces of tanks, hot metals, and the like; the heat load contributed by the surrounding hot air is secondary. No moisture is added to the air so that there is no loss in the evaporative cooling capacity of the atmosphere. The requirements for sweating and evaporation are increased, however, because of the added radiant and convective loads. For men exposed to such conditions, heat balance is maintained by the evaporation of sweat. (*2*) In the *warm-moist* industries, such as laundries, dye houses, and deep mines with extensive use of water for dust control, water vapor is added to the air from wet processes or as escaping steam. Relatively little sensible heat escapes, but evaporative cooling capacity is greatly reduced. In consequence, the worker may be unable to dispose of his metabolic heat plus the small additional heat gained from the environment.

The amount of heat or water vapor added to the environment in the hot industries is usually substantial so that it is not economically feasible to provide sufficient cooling of the air to offset completely the added thermal load. Thus, the comfort standards that have been established for sedentary workers in air-conditioned offices and light industries (Chapter VIII) do not necessarily apply to the design of heat-control measures for the hot industries. Different standards, above the limits of simple comfort, are required and these will vary in respect to the physiological and psychological criteria on which they are based, depending on the kind of industry and the nature of the work. The level of heat exposure must be kept within safe limits to prevent serious physiological disturbance or injury to health. It will be necessary to go further toward the comfort zone in certain industries where impairment of efficiency and other physiological disturbances interfere with effective operation.

I. Effects of Heat on Man

The varying effects of heat on employees are portrayed in Figure 1.[1] Increasing degrees of psychological disturbance are noted as the level of thermal stress goes up above the comfort zone, and some of the well-known consequences are noted on the chart. These range from purely subjective discomfort to demonstrable impairment of efficiency in the performance of mental tasks. A further increase in heat load results in a higher order of psycho-physiological disturbance with an increase in frequency of errors, higher accident frequency, and reduced efficiency in the performance of skilled physical tasks. At still higher levels of exposure there is a definite loss of work capacity with disturbance of physiological well-being, strain upon the heart and circulatory system, and overloading of the mechanisms of water and salt balance in the body. These disturbances culminate in acute heat exhaustion or stroke and may terminate fatally.

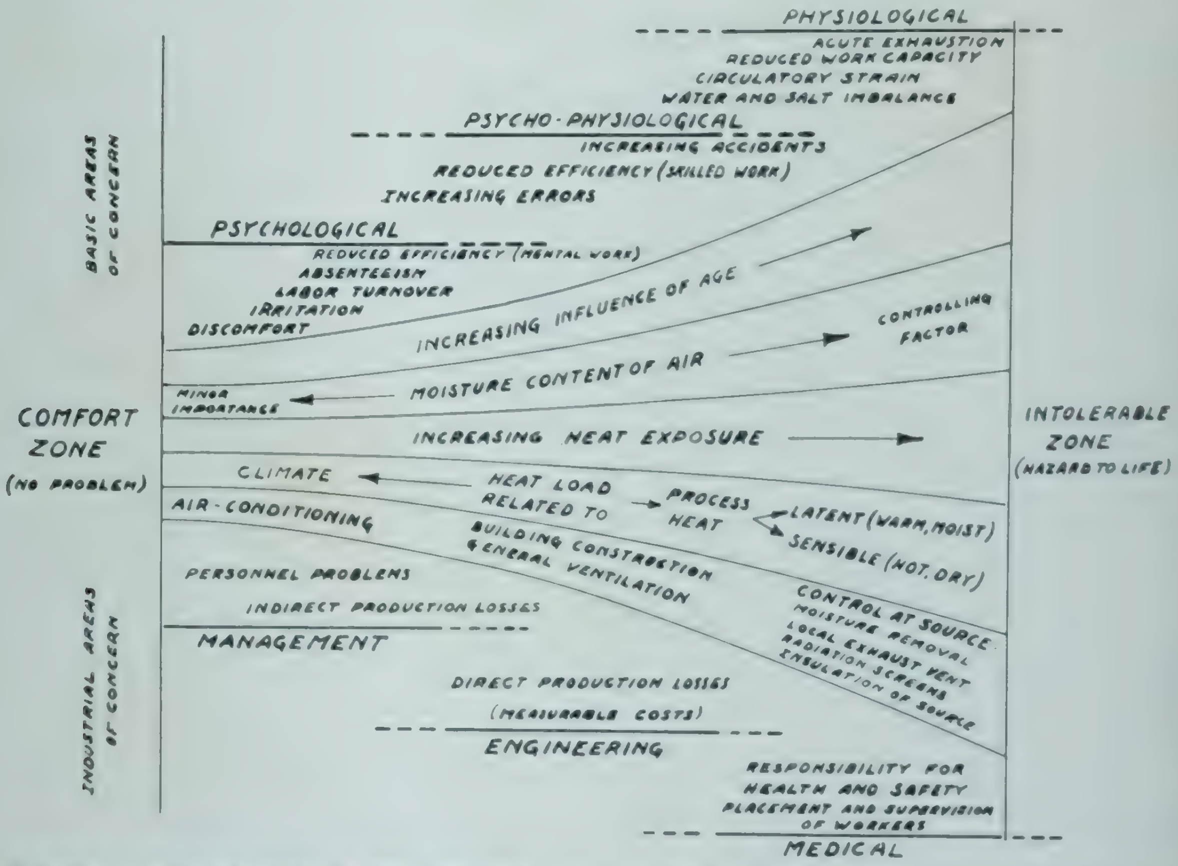

Figure 1. Effects of heat on man, ranging from no effect (comfort) to extreme physiological breakdown (heat exhaustion, stroke, death).

In parallel with the three (overlapping) categories of response to heat, psychological, psycho-physiological, and physiological, the areas of primary responsibility for fixing limits of exposure are also shown on the chart. At the lower levels of thermal stress there is no demonstrable effect on health. The consequences of heat exposure are reflected in personnel problems and indirect production losses. In the middle zone, still without evidence of direct ill-effects upon employees, the cost of thermal stress is reflected in increased production costs, and these must be compared with cost of heat control to determine the extent to which thermal stress is to be reduced. This is the concern of industrial and production engineering. It is the top zone of physiological disturbance with which we are concerned here. Thermal standards are required that will insure safe working conditions for the normal industrial population working at the rates and for the periods of time necessary to the performance of their tasks without physiological distress or impairment to health.

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[1] T. F. Hatch, Standards for industrial heat control, in symposium on "Man and His Relationships to Air," *Heating, Piping, Air Conditioning*, **23**, 140–142 (April, 1951).

II. Physiological Limits of Heat Exposure

Body heat balance is a physiological requirement for comfort and health. Under normal conditions of comfort, the rate of heat production (metabolism) is just balanced by heat loss to the environment (see Chapter VIII). This comfortable balance is maintained without active sweating and with optimum skin and deep-body temperatures. An increase in heat production with work must be offset by an equal increase in rate of heat loss, which is accomplished by sweating and evaporative cooling. In environments above skin temperature, heat is brought to the body by radiation and convection, and this quantity together with the metabolic heat must be eliminated by the sole remaining avenue, evaporative cooling. Owing to his flexible sweating mechanism, man can dispose of substantial amounts of heat in this manner. An upper limit of evaporative cooling is reached, however, when the body surface becomes fully wetted.[2] If the metabolic heat plus that received from the environment exceeds the maximum evaporative capacity, the body must heat up. With the rise in skin temperature the external heat load goes down and evaporative cooling capacity increases so that thermal balance may be re-established at an elevated body temperature. A modest rise is physiologically acceptable, but any substantial increase in body temperature is accompanied by serious strain.

A. HALDANE'S WET-BULB TEMPERATURE LIMITS

The necessity to maintain heat balance at an acceptable level of body temperature has long been recognized as one criterion for fixing limits to heat exposure. Early observations were made by Haldane in 1905.[3] He defined the limit of endurance as the most extreme heat exposure that could be withstood without abnormal rise in body temperature. For the clothed, resting man, not especially acclimatized, the maximum endurable condition for sustained exposure was 88° F. for still air saturated with moisture. Higher air temperatures were found acceptable only when the moisture content was lowered to increase evaporative cooling and thus offset the hotter air. Haldane demonstrated the benefits of air movement, reporting that with 170 f.p.m. air velocity instead of still air, the endurable temperature of saturated air was raised from 88 to 93° F. A moderate work rate was found to lower the acceptable level 10° to 78° F. for saturated air. Reasoning that the wet surface of the body and clothing would act like the wet-bulb thermometer, Haldane suggested that environments with varying dry-bulb temperatures but having the same wet-bulb temperature would be thermally and physiologically equivalent. Thus, to maintain heat balance without abnormal rise in body temperature, Haldane recommended the following maximum temperatures for clothed men not especially acclimatized: (*1*) resting, in still air—88° F., wet-bulb temperature; (*2*) resting, 170 f.p.m. air velocity—93° F., wet-bulb temperature; (*3*) moderate work, still air—78° F., wet-bulb temperature.

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[2] A. P. Gagge, A new physiological variable associated with sensible and insensible perspiration, *Am. J. Physiol.,* **120,** 277 (1937).

[3] J. J. Haldane, The influence of high air temperatures, *J. Hyg.,* **5,** 494 (1905).

B. EXPOSURE LIMITS IN TERMS OF EFFECTIVE TEMPERATURE

Later, with the development of the ASHAE Effective Temperature scale (Chapter VIII), it was found that physiological limits to prevent abnormal rise in body temperature could be expressed, for different levels of activity, in terms of this scale, which combines temperature, humidity, and air motion into a single thermal index. The rate of increase in temperature and in pulse rate rose sharply in the resting man when the effective temperature, ET, was above 90° F., and the break occurred at a lower ET level for the working man. In still, saturated air the ET is the same as the wet-bulb temperature, so that a recommended ET of 90° agrees well with Haldane's earlier suggestion of 88° F., wet-bulb, for a resting man. For sedentary work (500 B.t.u./hr.) an ET of 85° was found acceptable, whereas for heavy work (1800 B.t.u./hr.) the ET of the environment should not exceed 80° F.[4] Within these limits body temperature remains below 101° F. and the heart rate less than 125 beats per minute over a normal working day.

C. PHYSIOLOGICAL LIMITS BASED ON PERFORMANCE ABILITY

At the Armored Medical Research Laboratory Eichna and associates[5] obtained more extensive data on the upper limit of tolerance to heat. Observations were limited to young men in good physical condition and well acclimatized to heat. Tests involved 4 hours' exposure (nude) walking at 3 m.p.h., equivalent to 300–400 f.p.m. air velocity, carrying a 20 pound pack (about 1200 B.t.u./hr.). The

[4] C. P. Yaglou (Chairman, APHA Committee on Atmospheric Control), Thermal standards in industry, *Am. Public Health Assoc. Yearbook, 1949–50*, pp. 131–143.

[5] L. W. Eichna, W. B. Bean, and W. B. Shelf. The upper limits of environmental heat and humidity tolerated by acclimatized men working in hot environments, *J. Ind. Hyg. Toxicol.* **27**, 59 (1945).

demonstrated ability or inability to complete the assigned task during the 4-hour period was used as the criterion of tolerance. "Relatively easy" environments fell along line No. 1 on the psychrometric chart shown in Figure 2. The work in these environments was easily accomplished without great effort or complaint and with all subjects alert at the completion of the work period and seemingly capable of continuing indefinitely. "Difficult" environments, in which all subjects completed the work, but only with great effort and with evidence of approaching exhaustion, are shown on a parallel line, No. 2, in Figure 2. A third parallel line defines "Impossible" environments, in which the work could be carried on only with real danger to health. The narrow differences in moisture content of the air between easy, difficult, and impossible environments are especially to be noted.

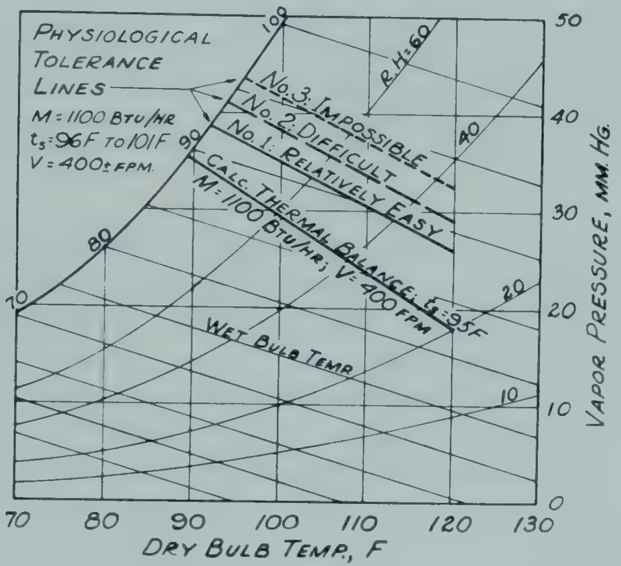

Figure 2. Lines of maximum physiological tolerance and calculated line of thermal balance, plotted on psychometric chart. Air and wall temperatures equal; air velocity, 400 f.p.m.; metabolic rate, 1100 B.t.u./hr.

D. MAXIMUM PERMISSIBLE SWEAT RATE

There are practical objections to defining limits to heat exposure in terms of environmental factors only, since a different standard is required for each work rate. McArdle *et al.*[6] have proposed using the sweat rate as a single index of heat stress to include both the work load and the external heat load. They recommend 4.5 liters output in four hours as the maximum permissible rate consistent with physiological well-being for repeated exposures to heat for acclimatized young men in good physical condition. A chart has been developed[6] from which the

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[6] B. McArdle, W. Dunham, H. E. Holling, W. S. S. Ladell, J. W. Scott, M. L. Thompson, and J. S. Weiner, *The Prediction of the Physiological Effects of Warm and Hot Environments.* Royal Navy Personnel Research Committee, Med. Research Council, H. M. Stationery Office, London, October, 1947.

"predicted 4-hour sweat rate" (P4SR) can be obtained for any environment combination of air, mean radiant and wet-bulb temperatures and air velocity, and for different levels of work. From this chart one can determine the acceptability of a hot environment or the degree of improvement necessary to secure a predicted sweat rate within the acceptable limit.

E. CALCULATED LIMITS OF HEAT EXPOSURE TO MAINTAIN THERMAL BALANCE

From the development of the concept of "partitional calorimetry" at the John B. Pierce Laboratory of Hygiene,[7] Gagge, Herrington, and Winslow[8] defined the upper limit of tolerable heat exposure as any maximum thermal environment in which body heat balance is just maintained (for a given work rate) without significant rise in skin temperature. Using the simple heat balance equation:

$$M \pm R \pm C = E$$

where M is metabolic rate, R the radiant heat exchange, C the convective heat exchange, and E the heat loss by evaporation, Haines and Hatch[9] outlined a physical method for evaluating the magnitude of heat stress imposed on employees in the hot industries. This procedure, which makes use of the coefficients of heat exchange by radiation, convection, and evaporation obtained on nude men at the Armored Medical Research Laboratory,[10] may also be used in determining the most effective control measures and the extent of controls required to bring environmental conditions within the limits necessary to maintain heat balance (with skin temperature 95° F.). For a man of average size the approximate heat balance equations are:

$$E_{\text{required}} = M + 22\ (t_w - 95) + 2\sqrt{V}\ (t_a - 95)$$

and

$$E_{\text{maximum}} = (10.3V)^{0.4}\ (42 - VP_a)$$

E_{required} is the necessary evaporative cooling rate to maintain balance; E_{maximum} is the maximum evaporative cooling rate for man when the body is fully wetted. The other symbols are: t_w = mean radiant temperature of the surrounding walls in ° F.; t_a = air temperature in ° F.; V = air velocity in f.p.m.; VP_a = vapor pressure of the water vapor in the air in mm. Hg. The values 22, $2\sqrt{V}$, and $10.3V^{0.4}$ are the coefficients of heat transfer for radiation, convection, and evaporation, respectively, each multiplied by the effective surface area of the body. The vapor pressure of water at the skin temperature of 95° F. is 42 mm.

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[7] C.-E. A. Winslow and L. P. Herrington, *Temperature and Human Life*, Princeton University Press, Princeton, N. J., 1949.

[8] A. P. Gagge, L. P. Herrington, and C.-E. A. Winslow, Thermal interchanges between the human body and its atmospheric environment, *Am. J. Hyg.*, **26**, 84 (1937).

[9] G. F. Haines and T. F. Hatch, Industrial heat exposures, evaluation and control, *Heating and Ventilating*, **49**, 93–104 (November, 1952).

[10] N. Nelson, L. W. Eichna, S. M. Horvath, and T. F. Hatch, Thermal exchanges of man at high environmental temperatures, *Am. J. Physiol.*, **151**, 626 (1947).

The external heat load, $R + C$, may be calculated from the difference between the "operative" temperature[7] and the skin temperature:

$$R + C = K_0\ (t_0 - 95)$$

where

$$K_0 = 22 + 2\sqrt{V}$$

and

$$t_0 = \frac{22t_w + 2\sqrt{V}\ t_a}{22 + 2\sqrt{V}}$$

The Vernon globe temperature, t_g,[11] may be used in place of the calculated operative temperature. For any given combination of globe temperature, wet-bulb temperature, air velocity, and work rate, one may quickly determine the ratio, $E_{\text{req.}}/E_{\text{max.}}$ with the aid of the charts in Figure 3. Values of M for different work situations are given in Table 1. The thermal balance line for t_s (skin temperature) $= 95°$ F., $M = 1100$ B.t.u./hr., and $V = 400$ f.p.m., calculated on the basis of the above coefficients of heat transfer, is compared with Eichna's lines of maximum physiological tolerance in Figure 2.

TABLE 1

Estimates of Energy Metabolism for Various Types of Activity
(Values apply for a 154-pound man, and do not include rest pauses)

Activity	B.t.u./hr.
Sleeping	250
Sitting quietly	400
Light work	
Sitting, moderate arm and trunk movements (e.g., desk work, typing)	450–550
Sitting, moderate arm and leg movements (e.g., playing organ, driving car in traffic)	550–650
Standing, light work at machine or bench, mostly arms	550–650
Moderate work	
Sitting, heavy arm and leg movements	650–800
Standing, light work at machine or bench, some walking about	650–750
Standing, moderate work at machine or bench, some walking about	750–1000
Walking about, with moderate lifting or pushing	1000–1400
Heavy work	
Intermittent heavy lifting, pushing or pulling (e.g., pick and shovel work)	1500–2000
Hardest sustained work	2000–2400

F. PHYSICAL BASIS OF TOLERANCE LINES

Man's response to heat is complex, and relationships between magnitude of stress and physiological disturbance induced by the heat involve more than simple heat balance. Implicit in the establishment of tolerance limits, however, is the

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[11] H. M. Vernon, The radiation experienced in factories and houses, *J. Ind. Hyg. Toxicol.*, **19**, 498 (1937).

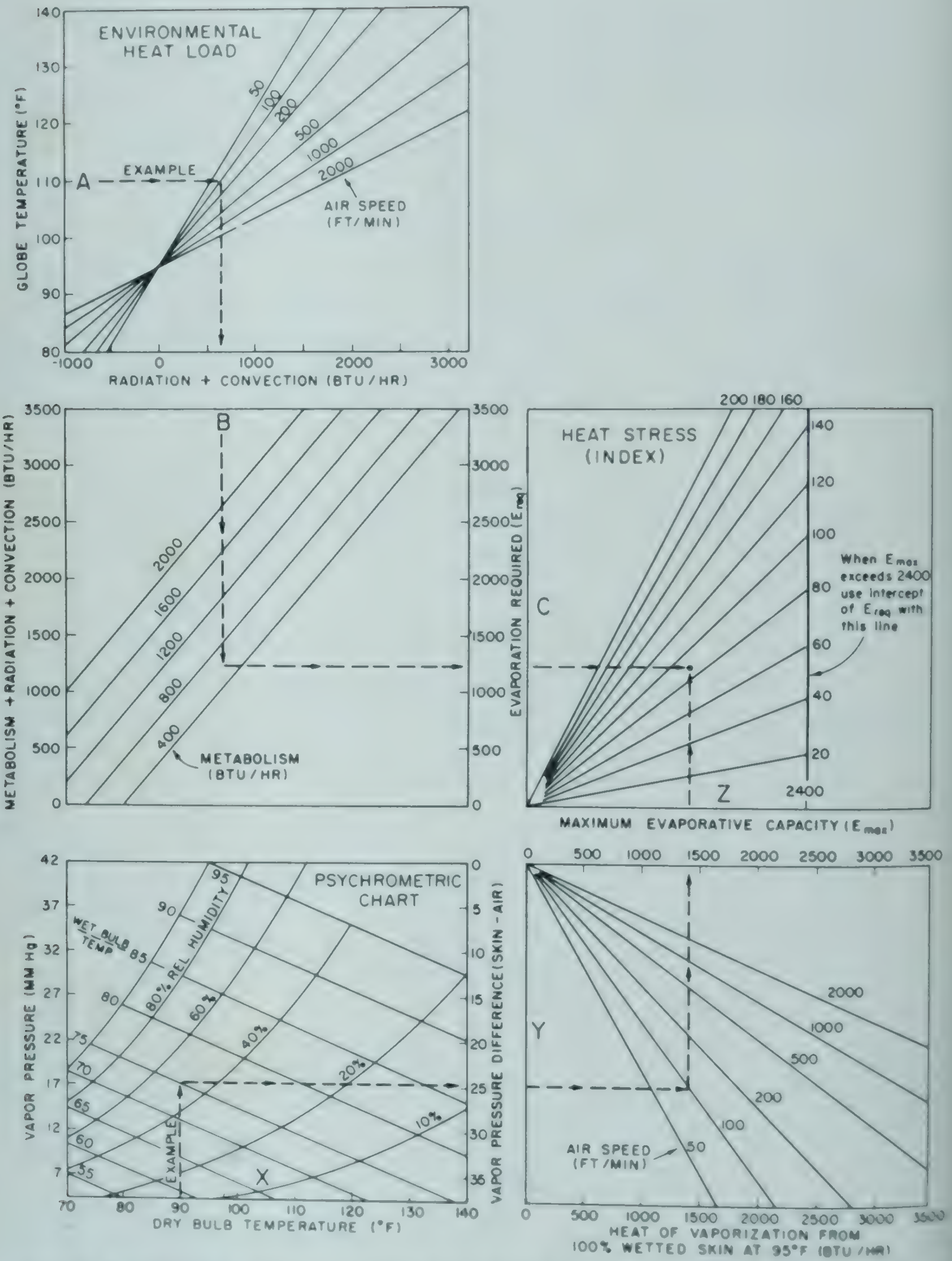

Figure 3. Flow charts for determining heat stress with example showing method of use. (M
Belding and Hatch.[12])

(*Explanation on facing page*)

assumption of direct relationships of sufficient simplicity to cover practical situations adequately. It is therefore of interest to examine the proposed limit lines that purport to combine the several factors into a single index to determine the physical basis, if any, in their apparent physiological equivalence.

Haldane's original proposal to use the wet-bulb temperature as a single thermo-physiological index was based more upon physical reasoning than physiological consideration. The completely wetted surface of man, according to this reasoning, should assume a temperature directly related to the wet-bulb temperature of the air. The latter bears a direct relation to the dry-bulb and dew-point temperatures of the air such that the rate of heat flow into the thermometer bulb by convection and radiation just equals the rate of heat loss by evaporation from the wet bulb. For the ordinary thermometer with a $^1/_4$-inch bulb, the convection coefficient is given by: $K_c = 0.5\sqrt{V}$. The radiation coefficient (independent of bulb size) has a value of $K_r = \pm 1.0$ for temperatures around body temperature. Since the psychrometer is whirled at considerable velocity, K_c is many times greater than K_r, which can therefore be neglected. Consequently, the slope of the wet-bulb temperature line on the psychrometric chart is:

$$\frac{\Delta \mathrm{VP}_a}{\Delta t} = -\frac{K_c}{K_e} = -0.27 \text{ mm. Hg/° F.}$$

The convection coefficient of a cylindrical body varies (approximately) inversely with the square root of the diameter. For man, therefore, K_c is much smaller than for the thermometer and for a nude man has been shown experimentally to be: $K_c = 0.11\sqrt{V}$. For $V = 1000$ f.p.m., $K_c = 3.5$, which is not much greater than $K_r = 1.0$ and, hence, the latter cannot be neglected in considering the balance between heat input, $C + R$, and heat loss, E. With lower velocities K_c is even closer to K_r, and in still air it is actually smaller. In practical terms, this means that the line of thermal equivalence in man will have a steeper slope on the psychrometric chart than does the wet-bulb temperature line.

Using the coefficients of heat exchange given above and assuming an air velocity of 400 f.p.m., the line of thermal balance has a slope of —0.66 compared with —0.27 for the wet-bulb line. Eichna's lines of physiological equivalence have a slope of —0.44, which falls between the slopes of wet-bulb line and calculated

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Procedure: *Enter A*, dropping vertical line from intercept of globe temperature with air speed; this gives combined heat loads of radiation and convection. Extend vertical line to *enter B*. At intercept with metabolism, draw horizontal line; obtain total heat load in terms of evaporation required for heat balance ($E_{\text{req.}}$). Extend horizontal line to *enter C*. *Enter X*. Draw horizontal line from intercept of dry- and wet-bulb temperature; obtain vapor pressure gradient between saturated skin at 95° F. and ambient air. Extend horizontal line to *enter Y*. At intercept with air speed draw vertical line; obtain maximum evaporation from wet skin at 95° F. ($E_{\text{max.}}$). Extend vertical line to *enter Z*. Proceed to intercept with horizontal line from C. (If $E_{\text{max.}}$ exceeds 2400, enter Z at 2400). *Read heat stress index value.*

Example: Globe 110, dry-bulb 90, wet-bulb 75, air speed 100, metabolism 600 (light arm work standing at bench). For solution follow broken lines: Heat stress = 90.

line of thermal balance (see Figure 2). The reason for the lesser slope compared with the calculated value for thermal balance is that the skin temperature of Eichna's subjects did not remain constant in all environments, but increased with air temperature sufficiently that the necessary evaporation took place in the extreme environments with a higher moisture content in the air than would otherwise have been permitted. These observations lend a good deal of support to the physical basis of the heat tolerance lines.

G. LIMITS OF HEAT EXPOSURE FIXED BY THERMAL BALANCE AND MAXIMUM PERMISSIBLE SWEAT RATE

In recognition of the physiological cost of sweating as well as the necessity for maintaining heat balance during sustained periods of heat exposure, Belding and Hatch[12] have combined these two limiting requirements to define a heat stress index that has a value of 100 when $E_{req}/E_{max} = 1.0$. This scale holds up to $E_{req} = 2400$ B.t.u./hr., which is just below McArdle's maximum acceptable sweat rate of 4.5 liters (equivalent to 2500 B.t.u./hr.) in 4 hours. In more severe environ-

TABLE 2

Physiological and Hygienic Implications of 6- to 8-Hour Exposures at Various Levels of Heat Stress[12]

Heat stress	Implications
0	No thermal strain.
10–30	Mild to moderate heat strain. Where a job involves higher intellectual functions, dexterity, or alertness, subtle to substantial decrements in performance may be expected. In performance of heavy physical work, little decrement expected unless ability of individuals to perform such work under no thermal strain is marginal.
40–60	Severe heat strain, involving a threat to health unless men are physically fit. Break-in period required for men not previously acclimatized. Some decrement in performance of physical work is to be expected. Medical selection of personnel desirable because these conditions are unsuitable for those with cardiovascular or respiratory impairment or with chronic dermatitis. These working conditions are also unsuitable for activities requiring sustained mental effort.
70–90	Very severe heat strain. Only a small percentage of the population may be expected to qualify for this work. Personnel should be selected (a) by medical examination and (b) by trial on the job (after acclimatization). Special measures warranted to assure adequate water and salt intake. Amelioration of working conditions by any feasible means is highly desirable, and may be expected to decrease the health hazard while increasing efficiency on the job. Slight indisposition, which in most jobs would be insufficient to affect performance, may render workers unfit for this exposure.
100	Maximum tolerable strain for fit, acclimatized young men.

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[12] H. S. Belding and T. F. Hatch, Index for evaluating heat stress in terms of resulting physiological strains, *Am. Soc. Heating, Air-Conditioning Engrs. Trans.*, **62**, 213 (1956).

ments, the heat stress index will be greater than 100 in proportion to the ratio: $E_{\text{req.}}/2400$. The value of the index may be obtained from the chart in Figure 3. A stress index value of 100 represents the maximum tolerable heat load for sustained (6–8 hours) exposure for acclimatized young men in good physical condition and engaged in elementary physical work. For older men or others with lowered physiological capacities, and in more demanding jobs requiring high degrees of skill and mental effort, the maximum level of heat stress must be set well below 100. The degrees of physiological and psychological stress associated with index values ranging from 0 (comfort) to 100 are suggested in Table 2, and these may be used as guides in the appraisal of heat exposures and in setting limits for industry.

III. Physical Evaluation of Hot Environments

The following examples[9] illustrate the application of the method of physical analysis to the evaluation of typical heat exposures.

Example 1. An extreme heat exposure was encountered in the Forming Department of a glass plant. Measured values of globe temperature, dry- and wet-bulb temperatures, and air velocity were: $t_g = 130°$ F.; $t_a = 100°$ F.; $t_{wb} = 80°$ F.; $V = 200$ f.p.m.; calculated $t_w = 177°$ F.[9] An average work rate was assumed equivalent to 960 B.t.u./hr.

Determine: (a) relative contributions of radiation and convection to the total imposed heat load and (b) the heat stress index.

Solution:

$$R = 22(177 - 95) = 1800 \text{ B.t.u./hr.} = 62\% \text{ total heat load}$$
$$C = 2\sqrt{200}(100 - 95) = 140 \text{ B.t.u./hr.} = 5\% \text{ total heat load}$$
$$M = 960 \text{ B.t.u./hr.}$$
$$E_{\text{req.}} = M + R + C = 2900 \text{ B.t.u./hr.}$$
$$E_{\text{max.}} = 10.3\ (200)^{0.4}\ (42\text{-}21) = 1550 \text{ B.t.u./hr.}$$
$$\text{Heat stress index} = E_{\text{req.}}/E_{\text{max.}} \times 100 = 187$$

The exposure is excessive and would lead to disaster if continued. In fact, the operator does not remain in the heat more than a few minutes to complete his task and then seeks relief.

This is a hot-dry exposure with 62 per cent of the total heat load imposed by radiation. Principal heat control measures must be directed toward the radiant heat sources.

Example 2. The following conditions were found in a hot wet mine: $t_g = 98°$ F.; $t_a = 95°$ F.; $t_{wb} = 85°$ F.; $V = 200$ f.p.m.; calculated $t_w = 106°$ F.; average work rate assumed = 800 B.t.u./hr.

Determine: (a) contribution of radiation and convection to total heat load and (b) heat stress index value.

Solution:

$$R = 22(106 - 95) = 240 \text{ B.t.u./hr.} = 23\% \text{ total heat load}$$

$$C = 2\sqrt{200}(95 - 95) = 0 = 0\% \text{ total heat load}$$
$$M = 800 \text{ B.t.u./hr.}$$
$$E_{\text{req.}} = 1040 \text{ B.t.u./hr.}$$
$$E_{\text{max.}} = 10.3\ (200)^{0.4}\ (42 - 28) = 1100 \text{ B.t.u./hr.}$$
$$\text{Heat stress index} = E_{\text{req.}}/E_{\text{max.}} \times 100 = 95$$

Thermal balance will be maintained in this environment. The exposure is just acceptable for a young acclimatized man. In practical mining operations, however, the stress should be lowered. This is a warm-moist environment in which evaporative cooling capacity is limited. An increase in the wet-bulb temperature to 89° F. would reduce $E_{\text{max.}}$ to 700 B.t.u./hr., thus making the environment wholly unacceptable even to young men in the best physical condition.

Example 3. The following measurements were made on a hot summer day in a glass factory: $t_g = 123°$ F.; $t_a = 103°$ F.; $t_{wb} = 80°$ F.; $V = 300$ f.p.m.; outside air temperature = 87° F.; calculated $t_w = 162°$ F.; M assumed = 960 B.t.u./hr.

Determine: (a) magnitude of stress and (b) magnitude of change required in each of the environmental factors to establish thermal balance.

Solution:

$$R = 22(162 - 95) = 1480 \text{ B.t.u./hr.} = 54\% \text{ total heat load}$$
$$C = 2\sqrt{300}(103 - 95) = 280 \text{ B.t.u./hr.} = 10\% \text{ total heat load}$$
$$M = 960$$
$$E_{\text{req.}} = 2720 \text{ B.t.u./hr.}$$
$$E_{\text{max.}} = 10.3\ (300)^{0.4}\ (42 - 20) = 1930 \text{ B.t.u./hr.}$$
$$\text{Heat stress index} = 140 \text{ (excessive heat exposure)}$$

$E_{\text{req.}}$ must be reduced by 790 B.t.u./hr. to attain thermal balance.

(*1*) Radiant heat has to be reduced as follows:

$$(1480 - 790) = 22\ (t_w - 95)\,;\ t_w = 127° \text{ F.}$$

The mean radiant temperature, t_w, must be reduced by 35° F.

(*2*) To obtain some improvement by reducing the air temperature, the convective load must be reduced to: (280 − 790) = −510 B.t.u./hr. Entering this value of C in the equation for convection exchange:

$$-510 = 2\sqrt{300}(t_a - 95)\,;\ t_a = 80° \text{ F.}$$

A reduction of 23° F. is therefore required in air temperature.

(*3*) Air velocity might be increased to bring about thermal balance, indicated by the following equations:

$$E_{\text{req.}} = 960 + 1480 + 2\sqrt{V}(103 - 95)$$

$$E_{\text{max.}} = 10.3\ V^{0.4}\ (42 - 20)$$

Equating $E_{\text{req.}}$ and $E_{\text{max.}}$ and solving for V, we get $V = 900$ f.p.m. Increasing the velocity to 900 f.p.m. raises C to 480 B.t.u./hr. and $E_{\text{req.}}$ goes up to 2920 B.t.u./hr.

Heat stress index = 2920/2400 × 100 = 120, which is excessive, even for a fit young man. This illustrates the fallacy in using "man-cooling" fans to combat extreme heat exposures.

(*4*) The reduction in humidity necessary to establish balance would be:

$$E_{\text{req.}} = E_{\text{max.}} = 2720 = 10.3\ (300)^{0.4}\ (42 - \text{VP}_a)\,;\ \text{VP}_a = 10\ \text{mm.}$$

This corresponds to $t_{wb} = 70°$ F. and RH (relative humidity) = 20%, compared with original value of $t_{wb} = 80°$ F. and RH = 37%. Since $E_{\text{req.}}$ exceeds 2400 B.t.u./hr., this is not a good solution because of the excessive sweating needed to secure thermal balance.

The calculations in Example 3 are of practical interest because they reveal the nature and magnitude of the corrective problem. The logical first step in control is obviously to reduce the radiant heat by more than 50 per cent, which has been shown to be easily attainable (see Table 3). Cooling the air is not economically feasible. Increasing the air velocity to 900 f.p.m. appears to be an easy solution. It is not an acceptable solution, however, since thermal balance can be attained only with an actual increase in heat load and a demand for excessive sweating. Reducing the humidity would be costly and also improper physiologically since $E_{\text{req.}}$ is excessive.

IV. Heat Control

Heat escaping into the environment from hot processes should be thought of as a contaminant, like dust or vapor, and measures for the control of heat fall into the same classes as do the different procedures for control of other atmospheric contaminants.

A. CONTROL AT SOURCE

In the application of local control measures, distinction must be made between the heat losses from hot bodies by radiation and those by convection. Since radiation varies with the fourth power of absolute temperature, it is clear that the larger share of heat loss from furnaces with high surface temperatures will be in the form of radiant heat. With a surface temperature of, say, 500° F., the radiation coefficient has a value of $K_r = 3.2$ B.t.u./ft.^{2}/hr./°F., compared with $K_c = 1.6$. Hence, 67 per cent of the heat loss will be by radiation. Only when the hot body is located in a strong forced air stream will the convection exchange equal or exceed the radiation output.

1. Insulation

Insulation of hot surfaces prevents the escape of sensible and radiant heat to the environment. Similarly, enclosing hot water tanks, covering drains carrying hot water, and continuous maintenance of joints and valves in piping to prevent loss of steam constitute direct measures for the control of latent heat in warm-moist industries. The extent to which such direct measures can be applied varies with the nature of the hot process but, obviously, elimination of all heat escaping to the environment is the most desirable action. As concern with the heat problem increases, interest in direct control at the source goes up; greater efforts are being made to isolate hot processes, and a growing tendency is seen to locate such equipment out of doors with only a roof shelter.

2. Radiation Shielding

Shielding against radiant heat is a primary measure for control of exposure, but until recently it was not generally employed. It has the flexibility that insulation lacks and can be designed to protect the exposed person rather than to minimize escape of heat from the hot body. *Reflecting* shields made of aluminum foil backed by insulating board or aluminum sheets may be employed. The substantial benefits from radiation shielding are demonstrated by the data[9] in Table 3. Such experimental results have led to extensive application of shielding in glass plants and other hot-dry industries. *Absorbing* shields of ordinary sheet steel also may be used. The radiant heat is absorbed and largely converted to convective heat with some re-radiated at a lower temperature. Absorbing shields may be constructed of two or three sheets separated by air spaces. Insulating materials are even better since the radiation temperature on the shielded side will be lower than on the hot side. *Water-cooled* shields absorb the heat, which is carried away with the water. *Transparent* shields are required where the view of the operation cannot be interrupted. For this purpose, chains may be employed to reduce the radiation in proportion to the area intercepted, and wire mesh screens are also

TABLE 3

Reduction in Radiation by Screening
(Single sheet of aluminum foil)

	Heat exchange by radiation (B.t.u./hr.)		
Test location	Without screening	With screening	% reduction in radiation
D4	2600	900	65
D6	2240	775	65
D7	1440	500	65
D10	2450	1010	59
D12	1460	560	62
D15	1850	775	58
D16	3150	825	74
A11	3525	1275	64
A12	2000	980	51
A14	2670	820	69
A15	1850	800	57

effective in the same way. Special heat-reflecting glass is available for windows in observation rooms and the like.

The radiant energy impinging on employees at most work locations is not uniformly distributed. It comes to them in concentrated amounts from certain directions with relatively little contribution from other quarters. The principal sources may be obvious so that shields can be interposed at the most effective points about the exposed persons. In other instances, it will be desirable to study the horizontal distribution of radiation intensity about the work station to determine the direction of major concern. For this purpose a directional radiometer is used,[13] which yields results as illustrated in Figure 4.

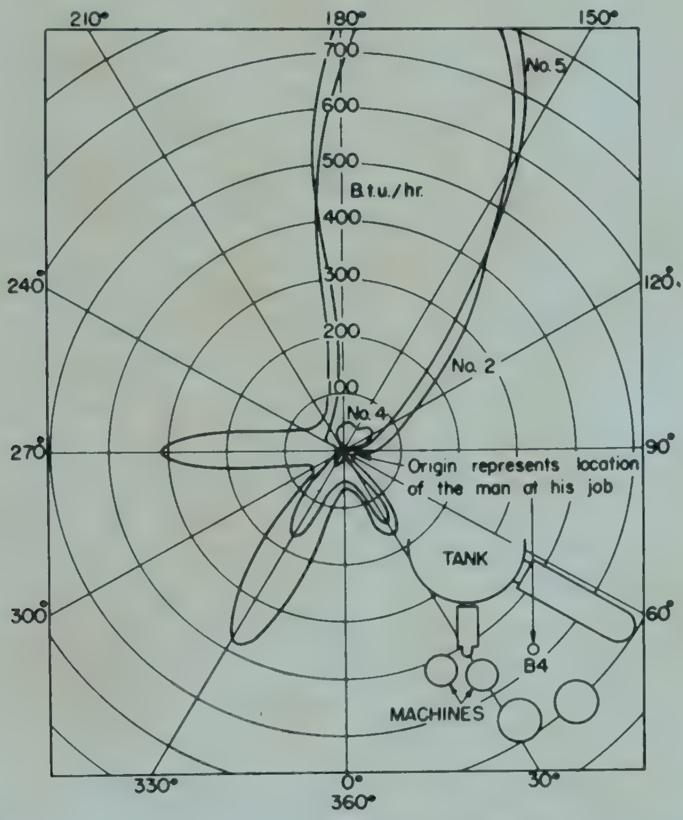

Figure 4. Variation in distribution of radiant heat intensity around work station in forming department of glass factory. (After Haines.[13])

3. Local Exhaust Ventilation

Canopy hoods with natural-draft or mechanical-exhaust ventilation are in common use over furnaces and similar hot equipment. The benefits are obvious, although it must be remembered that heat control by ventilation serves only to remove convective heat. Radiation shielding should be used as well to control the larger fraction of the total heat escaping from the process. The design of local exhaust hoods is considered in Chapter X.

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[13] G. F. Haines, *Analysis and Control of Hot Environments.* Industrial Hygiene Foundation of America, Pittsburgh, Pa., April, 1950.

B. GENERAL BUILDING VENTILATION

The most common means for heat removal in the hot industries is by general ventilation, making use of wall openings for the entrance of cool outside air and roof ventilation, commonly of the gravity type, for the escape of the heated air.

Although the higher fraction of heat loss from hot bodies is by radiation, this radiant heat is absorbed by building walls and other solid structures. These heated surfaces become sources of convective heat and also act as secondary reradiators. Eventually, the heat must be removed from the enclosed space by ventilation (except for losses through walls). General ventilation is therefore an essential part of the heat-control procedure; but it does not take care of direct radiant-heat exposures and, even in its secondary role, has failed to function as needed. A principal reason for this failure is that inadequate provisions are made for air ingress. Insufficient area of openings and poor location of inlets result in improper distribution of too little air within the building.

Convection flow around hot bodies is naturally upward. With an ideal system of general ventilation, combined with radiation shielding, the inlet air should be brought in near the floor level, be directed toward the workers, and then flow toward the hot equipment. In this way the coolest air obtainable is received by the workers before its temperature is increased by mixing with warm building air or circulation over hot processes. This air will then flow toward the hot equipment and as its temperature increases it will rise and escape through the vent openings in the roof. The combination of the air motion and the coolest air available will result in the maximum comfort for the worker that can be obtained without some method of artificially cooling the air. Contrary to general practice, provisions for proper distribution of the air supply should receive the same careful consideration as that given to the selection of exhaust equipment. Engineering reference works may be consulted[14] (see Chapter VIII).

C. LOCALIZED VENTILATION AND COOLING AT FIXED WORK STATIONS

Often practical considerations limit the effectiveness of heat control at the source and building size and shape and limitation in air supply make it impossible to bring the heat within acceptable limits throughout the work area. In such cases, local relief may be provided over limited areas immediately around separate work stations. Cool air is introduced in sufficient quantity to surround each worker with an independent atmospheric environment.

The local relief, or so-called spot cooling, system has two different functions depending upon the relative importance of the radiant and convective components in the total heat load. (*1*) If the load is primarily convective in the form of hot air immediately surrounding the employee, then the only function of the local relief system is to displace the hot air immediately around him with air of an acceptable temperature and velocity. If the air is available at a suitable temperature and is introduced without mixing with the hot plant air, no further cooling will be necessary. Such a system is not one of spot cooling in the sense of cooling the employee, but, rather, one of maintaining an acceptable working atmosphere around him, within the hot building environment. (*2*) When there is a significant radiation load, however, the local relief system must provide some actual cooling to offset it, since the radiant energy will penetrate through the local pool of air surrounding the employee. This means that the temperature of the supplied air will have to be low enough to make the convection component, C, negative in the heat load to offset R, the radiation component.

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[14] W. C. L. Hemeon, *Plant and Process Ventilation*, The Industrial Press, New York, 1955.

Air movement within the local relief zone is desirable to maintain adequate evaporative cooling; but, for the reasons outlined earlier, the use of high air velocities and high evaporative cooling to offset radiation is not desirable since the convective load is increased (where $t_a > t_s$) and with it there is a greater sweating demand. This is the objection to simple man-cooling fans, which are so widely used in industry.

A major problem in the design of local relief systems is to introduce the supplied air in such a way that minimum mixing takes place with the surrounding hot air. High velocity jets encourage mixing but are frequently necessary to "throw" the air into the work zone from an offside supply duct. The design of local relief facilities is dealt with in the ASHAE *Guide*[15] and by Small.[16] The performance of air jets blowing through air have been extensively studied,[17–19] and the findings should have useful application in the design of spot-cooling systems.

In situations of extreme heat, employees may be stationed inside an insulated and separately ventilated observation booth or relief room, to which they can return after brief periods of high exposure directly on the job. The practical usefulness of such a protected room will vary with the industry. Air-conditioned crane cabs are now in common use.

V. Supervision of Employees in Hot Industries

Although man's ability to withstand heat decreases sharply with age, experience in the hot industries is often better with older than younger employees. This is because the older and more experienced men have learned how to get along in heat. They regulate their work rate and balance periods of exposure with periods of rest in cooler environments. In this way, they keep their over-all exposure within tolerable limits. In contrast, young, inexperienced men are apt to continue to work in excessive heat to the point of exhaustion. Such individuals require supervision to avoid overexposure.

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[15] *Heating, Ventilating, Air Conditioning Guide, 1954.* American Society of Heating and Air-Conditioning Engineers, New York, 1954.

[16] B. R. Small, Heat relief in industry, *Iron Steel Engr.*, **29**, 71–77 (April, 1952).

[17] G. L. Tuve, Air velocities in ventilating jets, *Heating, Piping, Air Conditioning,* **25**, 181–190 (January, 1953).

[18] L. Helander, S. M. Yen, and R. E. Crank, Maximum downward travel of heated jets from standard long radius ASME nozzles, *Am. Soc. Heating, Air-Conditioning Engrs. Trans.*, **59**, 241 (1953).

[19] A. Koestel, Computing temperatures and velocities in vertical jets of hot or cold air, *Heating, Piping, Air Conditioning,* **26**, 143–156 (June, 1954).

A. SAFE TOLERANCE LIMITS AND INTERMITTENT REST PERIODS

In a review of thermal standards for industry, the APHA Committee on Atmospheric Comfort[4] presented the following summary of findings and recommendations respecting safe tolerance times and duration of intermittent rest periods for persons exposed to extreme heat:

Safe Tolerance Limits

The tolerance contours (Figure 5) have been constructed from joint studies by the American Society of Heating and Ventilating Engineers and the U. S. Bureau of Mines during 1922–1926. Safe tolerance time, for the purpose of this report, is defined as the average time required to raise the pulse rate to 125 beats per minute from initial rates of 70 to 80, and the rectal temperature to 101° F. from initial levels of 98 to 99° F. Symptoms of heat distress do not appear in healthy persons until the pulse rate rises well above 130 and the rectal temperature above 101° F., in exposure lasting more than one hour.

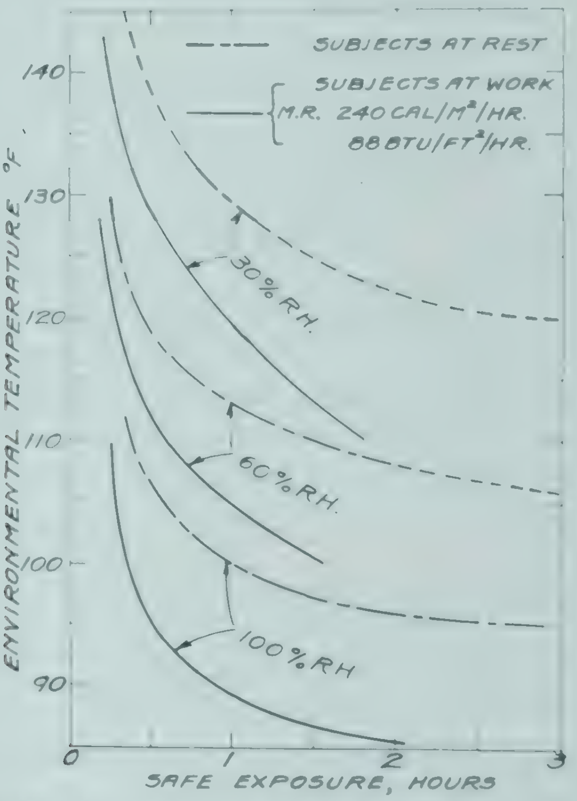

Figure 5. Permitted duration of heat exposure at rest and at work, for various environmental temperatures and relative humidities. (Courtesy *Am. J. Public Health.*)

> The proposed safe tolerance times are within the practical limits found in hot industries. . . . Long-continued exposure is known to lead to deterioration of performance and morale even in the fittest and well acclimatized individuals. Any safe limits that may be set must, therefore, allow for a wide margin of safety to be generally acceptable.

Intermittent Rest Periods

The length of recovery periods in a relatively cool environment will depend upon the rate and duration of work, the severity of heat, and on individual constitutional factors.

In laboratory experiments in which the rectal temperature was raised to between 100 and 102° F. by working for an hour or so in a saturated atmosphere of 95° F., the resting period required to drop the rectal temperature to 99° F. in a room at 85° F. dry-bulb and 50 RH was 30 to 40 minutes starting with 100° F. rectal temperature, and 60 to 90 minutes starting with 102° F. rectal temperature. Recovery of heart rate was much faster. However, after repeated exposures on the same day, neither the pulse nor the rectal temperature returned to normal but stabilized at higher levels.

As a rule, the workers themselves set the pace and the length of recovery periods in industries. In mines where temperatures approach 95° F., with humidities close to the saturation point, men work only one-half to one-third of the shift time, alternating short periods of work in the heat with rest periods of 40 to 45 minutes in cooler areas.

In aluminum and steel manufacturing processes in which environmental temperatures between 120 and 160° F. with relative humidities of 3 to 15% (ET, 90–100° F.) are encountered, men doing light duties work for about one hour and rest for an equal period, while those engaged in heavy occupations work for about 30 minutes and rest during the next 30 minutes.

B. MEDICAL SUPERVISION

Proper selection of persons best fitted for heat exposure, proper acclimatization before undertaking routine exposure to extreme heat, regulation of periods of work and rest, control of fatigue, and maintenance of an adequate intake of salt and water are essential measures for the protection of employees in the hot industries.

Preplacement and periodic examinations to detect circulatory and other physiological deficiencies help to keep unfit men away from excessive heat exposures. Acclimatization has dramatic benefits in preventing early cases of heat exhaustion. Maintenance of water and salt balance is essential to successful performance in the heat. The water supply should be conveniently located and the men encouraged to drink water beyond the dictates of thirst, which has been found in extreme heat exposures to be an unreliable index of water needs. The direct supply of salted water (0.1 per cent) has been found beneficial in hot industries (Chapter V).

There is evidence that the stress of physiological disturbances from causes other than heat is added to the heat stress, so that men with temporary respiratory infection, digestive disturbance, and other departures from normal health are more susceptible to heat exhaustion; during periods of such disturbances heat exposures should be limited. This is a responsibility of medical supervision, as is the continued observation of men exposed to heat to detect signs of long-term impairment, as in the circulatory system.

INDEX

A

Abattoir workers, skin hazards of, 471–72
Abrasive blasting, ventilation, 301
Abrasive-blasting respirators, 349, 353, 354
Absorption, of gases and vapors (curves), 157
  by ingestion, 162
  by inhalation, 150–61
  intermittent exposure effect on, 158–59
  through the skin, 162
Absorption coefficient, sound intensity, 641–43
Accident(s), heat and, 110–11, 790
  illumination and, 769–73
  prevention, human engineering in, 57–59, 109–10
Acetone, distribution coefficient, 154
  skin absorption, 162
Acids, organic, in air pollution, 424
  primary irritants, 449–50
Acoustical materials, 645
Actinic rays, and cancer, 469
Adsorption and weighing, gases and vapors, 187
Aerodispersions, *see* Air cleaning
Aeroembolism, 615
Aerosol(s), in air pollution, 424
  defined, 144
Age, decompression sickness and, 616–17
  dermatoses and, 446
  hand strength and, 99
  heat exposure and, 805–6
  noise and, 673
  residual capacity and, 390–91
Agricultural dusts, explosive limits, 563
  ignition temperatures, 561
Agricultural workers, skin hazards of, 469, 472
Air, analysis and sampling, 173–210
  city, dust in, 357
  composition of, 286
  make-up, 225–27
    inlets for, 297
    ventilation for radioactive materials, 738
  radioactive isotopes limits in, 704
  standard, ventilation, 328
Air cleaners, classification, 240–41
  combination systems, 272–74
    concentrators, 246, 274
    sequence of, 272–73
    two-stage, 263, 266, 274
  effectiveness, 239
  electric precipitators, 255–62
    single-stage high-voltage, 257–58, 261–62
    two-stage low-voltage, 260, 262–63
  factors in selection, 278–81
    cost analysis, 280–81
    fire or explosion hazards, 279–80
    incompatibilities, 278–79
    power requirements, 281
    versatility, 278
  filters, 247–55
    absolute, 255
    cloth, 253–54, 256–59
    gas or vapor adsorption, 255, 260
    impingement, 251–52
    paper, 252–54
    service of, 276–77
    viscous, 252–53
  performance specification, 237–40
    efficiency, 237–38
    referent difficulty of separation, 239–40
    separation degree, 238–39
  recirculation from, 229–30
  separators, 242–47
    baffle or impact, 246
    cyclone, 247–49
    gravitational, 242–44
    inertial, 244–45
    louvered or slotted, 246
    rotary centrifugal, 247, 250
    vortex, 247
  washers or scrubbers, 262–70
    liquid contact effectiveness, 264–66
    liquid disintegration, 265–66
    orifice-type, 268, 270
    packed towers, 268, 270
    selection of liquids, 263–64
    spray chambers or towers, 268–69
Air cleaning, 229–83
  aerodispersions, preparation of, 242
    properties of, 232
  applications, 229–30
    air-pollution control, 230
    indoor, 229–30

Air cleaning (*Continued*)
  continuous service arrangements, 275–77
  dry and wet systems compared, 270–72
  entrainment prevention, 274–75
    separator adhesives, 275
    turbulence, 274–75
  quality requirements, 230–32
  waste disposal, 277
Air conditioning, 211–28
  adding heat, 218–21
    controls, 221
    convection, 219–20
    radiation, 219–20
  air distribution, 225–28
  comfort chart for still air, 215
  dehumidification, 224–25
  Effective Temperature charts, 215–18
  electric precipitators for, 260, 262
  environmental control, 218–28
  humidification, 224
  odor control in, 287–88
  physical and physiological principles, 211–18
    human response to different temperatures, 213–14
  removing heat, 221–24, 227–28
    chilled coil system, 223–24
    cool air supply, 222
    evaporative cooling, 222–23
  thermal exchange between body and environment, 211–14
    convection, 211–12, 214
    evaporative heat loss, 211–14
    metabolism effect, 211, 213–14
    radiation, 211–12, 214
Air contaminants, *see* Contaminants
Air distribution, 225–28
Air flow, short-circuiting, 298
  velometer for, 210
Air horsepower, 328–29
Air motion in heat removal, 227, 804
Air movement and heat exposure, 792
Airplane workers, skin hazards of, 472
Air pollution, 413–42
  aerosols, acid gases, aldehydes emission, 424
  carbon monoxide in, 429
  community relations, 441
  control, 230, 429, 433–35
    curtailing operations, 434
    dilution, 433–34
    substituting materials and methods, 434–35
    temperature effects, 433
    zoning, 435
  diffusion mechanism, 439
  Donora disaster, 415–16
  economics of, 423–24
  effects on buildings, 422–23
  effects on people, 414–20
  effects on vegetation, 420–22
    indicator plants for evaluation, 422
    susceptibility of species, 421–22
  exhaust gases in, 424, 428, 429, 434
  fluorides in, 426–27
  health effects, acute, 414–18
  health effects, chronic, 418–20
  hydrogen fluoride in, 426–27
  hydrogen sulfide in, 416–17, 426
  incineration, 424, 434
  legislation, 435–38
  London disaster, 417–18
  meteorology and topography, 438–40
  Meuse Valley, 414–15
  organic acids in, 424
  oxides of nitrogen in, 424, 427–28
  ozone in, 428
  particle fall in cities, 429–32
  petroleum industry, 424, 426
  plant data evaluation, 440
  Poza Rica, 416–17
  recovery of pollutants, 423–24
  respiratory irritation and death from, 414–18
  sources and kinds, 424–29
  sulfur dioxide in, 424, 425–26
Air Pollution Foundation, 10
Air sampling and analysis, 173–210
Alcohols, skin absorption, 162
Aldehydes, in air pollution, 424
  primary irritants, 450
  skin absorption, 162
Alkalies, primary irritants, 449–50
Alkaloids, skin absorption, 162
Allergy, factor in dermatoses, 447–48
Alpha particles, 720, 730–33
  counting of, in radon measurement, 730–31, 732–33
  random rate of emission, 730–31
Alpha rays, in radium poisoning, 726
Altitude(s), critical, 614
  and decompression, *see* Atmospheric pressure, decompression
Aluminum, infrared protection, 720
  radiant heat control, 802

Aluminum abrasives, bauxite pneumoconiosis and, 400–1
Aluminum prophylaxis and therapy, silicosis, 394–96
American Association of Industrial Physicians and Surgeons, 6
American Conference of Governmental Industrial Hygienists, industrial ventilation manual, 319
  threshold limit values, 164–71
American Industrial Hygiene Association, 7
  Journal, 6
  Quarterly, 6
American Medical Association, first health congress, 6
  use of aluminum in silicosis, 395–96
  Archives of Industrial Health, 6
American Museum of Safety, 5
American Public Health Association, 5
  definition of silicosis, 369
  qualifications of industrial hygiene personnel, 10
  safe tolerance limits and rest periods, heat exposure, 806–7
American Society of Heating and Air-Conditioning Engineers, 340
  Effective Temperature Charts, 215–17
American Standards Association, 8
  atmospheric contaminants standards, 172
  committee to establish health standards, 172
  exhaust systems, fundamentals of, 308–9
  food-handling standard, 132
  hearing loss and noise exposure, 671
  plumbing standards, 124
  respiratory protective devices code, 350
  sanitation requirements, for change house, 137
    for chemical closets and privies, 138–39
    for drinking fountains, 118–19
    for eating space, 130–31
    for retiring rooms for women, 139
    for toilet facility, 137
    for toilets, 138
    for washing facilities, 139
Amines, primary irritants, 450
Ammonia, determination, 183
Ammonium picrate, determination, 184
n-Amyl alcohol, distribution coefficient, 154
Analytical methods, selection, 173–74
Anemia, in radium poisoning, 723, 727, 728
Anesthetics, defined, 146
Aniline, and cancer, 468
  skin absorption, 162
Anthracosilicosis, *see* Coal workers' pneumoconiosis
Anthracosis, *see* Coal workers' pneumoconiosis
Anthropometric data, application of, 64–82
  average values, 66–68
  correlations, 68, 70, 82
  percentiles, 68–70, 77
  sources of, 82
  standard deviation, 68
Anthropometric measurements, arm reaches, 72–77
  dynamic, 70–82
  leg reaches, 77–78
  seated eye level, 71–72
  seating dimensions, 78–82
  static, 64–70
  traditional, 64–66
Anthropometry, 64
Antimony salts, skin absorption, 162
Arc welding, effect on lips, 501
Arm reaches, 72–77
Arsenic, effect on skin, 487, 490, 491
Arsenic salts, skin absorption, 162
Asbestos, permissible concentration, 399
Asbestos bodies, 399
Asbestosis, 397–400
  control, 399
  lung cancer and, 398
  pathology and x-ray findings, 398–99
  symptoms, 398
Asbestos warts, 493
Ascent, and decompression, *see* Atmospheric pressure, decompression
Asphalt and pitch workers, skin hazards of, 468, 472
Asphyxiants, defined, 145
Atmosphere (*see also* Contaminants; Gases, atmospheric), composition, 143, 581
  temperature, and pressure effects, 589–91
Atmosphere chart, standard, 583
Atmospheric pressure, 584–86
  decompression, 601–6
    bubble formation, 602–4, 615–16
    effect on ear, 601
    following ascent, 607–11
    intestinal gases effect, 601–2, 610
    lung rupture, 602
    mechanical effects, 601–2
    rate, 604–6
    sinus effects, 601, 609–10

Atmospheric pressure (*Continued*)
  decompression sickness, 604, 614–17
  descent from altitudes, 618–19
  effects, 579–620
  effects of high and low compared, 619–20
  increased, effects, 594–606
  low maintained, 611–17
    acclimatization to, 617
    effect on lungs, 613
    hypocapnia, 612–13
    hypoxia, 611–12
  mechanical effects on body, 594–96
  positive maintained, 597–601
    circulation effects, 598–99
    body tissue saturation, 597–98
    inert gas effects, 599–600
    oxygen poisoning, 599
    subjective responses, 601
    temperature and humidity effects, 600
  reduced, effects of, 606–19
  sinus effects, 594–95
Atomic Energy Commission, 705, 739
  decontamination factor, 240
Audiogram, 660–61
Audiometer, 657–59, 660
  calibration, physical, 663–64
    psychophysical, 664
  description of, 661–63
  screening type, 661–62
Audiometer room design, principles of, 665–66
Audiometric booths, examples of, 667
Audiometric programs, personnel for, 668
Audiometry, speech, 666, 668
Auditory displays, 92
Averages, statistical, 32–33, 66–68

B

Back rest (*see also* Seating dimensions), 81
Bacteria and other microorganisms, evaluation, 210
  sampling, 209–10
Bacterial food poisoning, 129–30
Bakers, skin hazards of, 472
Bar, sound pressure unit, 623–24
Baritosis, roentgenogram, 379
Bark dust, explosibility, 549, 563
Bausch and Lomb dust counter, 193
Bauxite pneumoconiosis, 400–1
Bends, in caisson workers, 598, 600
  control by oxygen, 605
  during ascent, 607, 608–9
  during decompression, 603–4, 606
  following ascent, 615–16
  and muscular exercise, 616
Benzene, blood absorption (curve), 157
  blood saturation, 156
  distribution coefficient, 154
  effect on skin, 494
  elimination (curve), 158
  skin absorption, 162
Beta rays, 720
Biologic agents and dermatoses, 453–54
Biological specimens, 26, 46
  records of, 23–26
Biomechanical factors in control operations, 94–99
Bismuth salts, skin absorption, 162
Blood, arterial and venous vapor concentration difference, 156–57
  carbon dioxide in, 149
  carbon dioxide dissociation curves of man, 592
  complete circuit time, 150
  distribution coefficients of gases and vapors, 154–55
  oxygen in, 149
  oxygen dissociation curves of man, 592
  volume in man, 150
Blood counts, index of radiation injury, 706, 707
  in radium poisoning detection, 727
Blowers, fans, exhausters, 326–29
Body measurements, *see* Anthropometric data; Anthropometric measurements
Body movements, range, 94–96
  rate and accuracy, 96–97
Body temperature, physical and physiological principles, 211–18
Boilermaker's deafness, 621
Breath, garlic odor, 503
Brick, radiation protection coefficient, 717
Bricklayers, skin hazards of, 472
Brightness, factor in visibility, 745
  sensitivity to, 756
  and vision, 752–55
Brightness contrast, 753
British Occupational Hygiene Society, 12
Bronchioles and alveoli, 147, 363, 365
Bubble formation, in decompression, 602–4, 615–16
Building material, radiation protection coefficient, 717
Butadiene, explosion control, illustrated example, 540–41

Butchers, skin hazards of, 471–72

C

Cabinetmakers, skin hazards of, 472
Caisson workers, 601–2, 604
  "bends" in, 598, 600
  decompression for, 605–6
Can conveyors, noise control of, 681–82
Cancer, aniline and, 468
  coal tar and, 468
  heat and, 469
  lung, in asbestosis, 398
    and chromium, 468
    and radon, 728
  petroleum and, 468
  radium and, 469
  skin, incidence, 468–69
    prevention, 469
  x-rays and, 469
Candlepower, defined, 745
Candy makers, skin hazards of, 472
Canister, color code, 345
  type N, cross-section, 346
Canning, skin hazards in, 472–73
Capture velocity, 306–9
Carbon dioxide, dissociation curves of man, 592
  exhalation, 287
  in explosion prevention, 539–41, 556–57
  hypocapnia at low pressure, 612–13
Carbon dioxide absorbents, paralyzed by alcohol, 352
Carbon disulfide, blood absorption (curve), 157
  blood saturation, 156
  distribution coefficient, 154
  elimination (curve), 158
Carbon monoxide, in air pollution, 429
  indicators, 181–82, 184
  poisoning, skin color, 480, 486
Carbon tetrachloride, in explosion prevention, 540, 544
  jaundice from, 487
Carpenters, skin hazards of, 472
Carrier gas, properties in air cleaners, 232–33
Cement workers, skin hazards of, 472
Centrifugal scrubbers, 247, 250, 269
Centrifugal separators, 244–45
Chain saw, noise control of, 686–88
Chipping operations, noise control of, 682
Chloracne, 493
Chlorinated hydrocarbons, effect on eyes, 498
  skin absorption, 162
  use in explosion prevention, 542–44
Chromium, and lung cancer, 468
Chutes, hoppers, and tote boxes, noise control of, 679–80
Circulation, blood volume, 150
  pressure effects, 599
  regulation of, 149–50
  variables affecting, 150
Cleaners, air, *see* Air cleaners
Climate, and air pollution, 438–40
Clothing, protective, 462–64, 739
Coal dust, explosibility, 549, 552–53, 554, 555, 563
Coal tar, and cancer, 468
Coal workers' pneumoconiosis, 404–11
  emphysema in, 390, 409, 410
Coffee dust, explosibility, 549
Color, in coding radioactive sources, 711
  in equipment, 87
  in lighting, 755
Combustible gas indicators, in air analysis, 181
  in explosion control, 548
Combustion devices, in air analysis, 181–82, 185–87
Comfort chart for still air, 215
Concentration, atmospheric contaminant, units of measurement, 150–52
    allowable, 164–71
Concrete, in gamma ray protection, 710
  radiation protection coefficient, 717
Congress on Industrial Health, 6
Conjunctivitis, ultraviolet exposure, 788
Contaminants, air, in air cleaner design, 233–37
    field sampling record, 30–32
  amounts found in air cleaning, 234
  atmospheric, absorption, distribution, and elimination, 150–61
    allowable concentrations, 164–71
    modes of expressing concentration, 150–52
    sampling and analysis, 173–210
  classification, 143–46
  units of measurement, 150–52
Contamination, radioactive, removal of, 712–13
Contrast, factor in visibility, 745
  in visual acuity, 747
Control(s), advantages of "expected" relationships, 100–3
  biomechanical factors in, 94–99

- Control(s) (*Continued*)
    - body movement range, 94–96
    - body movement rate and accuracy, 96–97
    - body positions, forces in, 96
    - hand accuracy, 97–98
    - hand strength and handedness, 98–99
  - design, emergency controls, 106
    - foot controls, 106–7
    - friction and inertia, 105
    - gear ratio, 104–5
    - location, 99–100
    - movement, direction of, 100–3
    - platform stability, 105–6
    - principles, 99–107
    - shape, 103
    - size, 103–4
  - equipment, 93–108
  - heating systems, 221
- Convection, and heat exchange, 211–12
  - in heat supply, 219–20
  - heat transfer coefficient for, 794
- Convection coefficient, of cylindrical body, 797
- Conversion factors and useful equivalents, xv
- Conversion table, milligrams per liter to parts per million, xvi–xvii
- Conveyor, belt, 318, 320
- Conveyors for small parts, noise control of, 682
- Cooling, evaporative, 222–23, 227–28
  - mechanical, in heat removal, 228
- Copper salts, skin absorption, 162
- Cork dust, explosibility, 549, 563
- Corn products, explosibility, 549, 554, 556, 558, 559, 563
- Corpuscular radiation, 720–22
- Correlations, statistical, 35, 68, 70, 82
- Cotton mills, explosion hazards, 549
- Counting dusts, *see* Dust, counting
- Cristobalite, in diatomite, 402–3
    - permissible concentration, 404
- Critical altitudes, 614
- Curie, defined, 707

D

- DallaValle's equation, ventilation, 304–6
- Damage-risk criteria, in noise control, 674–75
- Dead space, 147–48
- Death, accident cause of, 57
  - from air pollution, 414–18
  - genetic, 698–700
- Decibel, intensity level unit, 632–33
  - sound pressure level unit, 636
- Decompression, *see* Atmospheric pressure, decompression
- Decompression sickness, 614–17
  - age and linear density effects, 616–17
  - recompression for, 617–19
- Decontamination factor, as index of air cleaning, 240
- Degreasers, ventilation, 314–15
- Dehumidification, 224–25
- Density, defined, 582
- Dermatoses, 443–78
  - actual causes, biologic agents, 453–54
    - chemical, 449–53
    - mechanical, 448
    - physical, 449–50
  - clinical types, 454–55
  - diagnosis, 455–61
  - incidence, 444–45
  - methods of investigation, 469–71
  - patch tests, 455, 457–61, 471
    - complications, 460–61
    - interpretation and reading, 459–60
    - technique, 457–59
  - predisposing causes, 445–48
    - age, 446
    - allergy, 447–48
    - perspiration, 447
    - race, 446
    - season, 446–47
    - sex, 446
    - skin disease, 447
    - uncleanliness, 447
  - prevention, 461–67
    - cleanliness, 464–65
    - pre-employment examination, 461–62
    - protective clothing, 462–64
    - protective ointments, 465–67
  - primary irritants, 449–51
  - sensitizers, 451–53
  - treatment, 467–68
  - of types of workers or occupations, 471–78
- Design, control, 94–107
  - duct, 329–40
  - equipment, 58–59, 63–64, 67, 83–108
  - kitchen, 132–33
  - visual principles of, 83–91
- Deviation, average, 34
  - quartile, 34
  - standard, 34–35
- Dials, design principles, 89–91

  multirevolution, 91
  pointer, 91
  scale markings, 89–91
  shape, 89
  size, 89
Diaphragms, release, explosion control, 546–48
Diatomaceous earth, industrial uses, 402
Diatomaceous earth pneumoconiosis, 401–4
  pathology and x-ray findings, 403–4
Diatomite, cristobalite in, 402–3, 404
  permissible concentration, 404
Diatomite industry, engineering control, 403
  U. S. Public Health Service survey, 402–4
Diethyl ketone, distribution coefficient, 154
Dimethylaniline, skin absorption, 162
Dinitrobenzene, skin absorption, 162
Dinitrotoluene, skin absorption, 162
Dispersion, statistical, 34–35
Displays, auditory, 92
  design principles, 89–91
  factors in visibility of, 84–87
    color, 87
    contrast, 84–85
    illumination, 85–86
    size, 84
    time of exposure, 86
  kinesthetic, 93
  tactual, 92–93
  visual, 83–91
    check, 87
    qualitative, 88
    quantitative, 88
Distribution coefficients, 154–55
Donora disaster, 415–16
Dry ice, in explosion prevention, 540
Duct(s), dampers for, 339
  design, exhaust systems, 329–40
    friction losses, 332–39
  flexible, 339
Dunn cell, for dust counting, 197
Dust (*see also* Explosions), chemical analysis, 204–5
  in city and country air, 357
  classification, human body effects, 360–62
  composition in fibrosis, 369–72
  concentrations and particle size, 359–60
  counting, 196–201
    choice of chamber, 196
    cleaning methods, 196
    dark-field vs. light-field, 198–99
    impinger samples, 196
    konimeter samples, 200
    light-field, 197–98
    making and computing, 198
    microprojector, 199
    Owen's jet samples, 200–1
    preparing sample, 197
    sample dilution, 196
    Sedgwick-Rafter cell, 196–97
  defined, 144
  entry and action, 160–61
  explosibility, composition effect, 551–53
    concentration effect, 555–56
    humidity effect, 557, 558
    ignition source type, 557
    laboratory data, 558–69
    oxygen effect, 556–57
    particle size effect, 553–54
    shape and surface effect, 554–55
    types of dust, 549–64
  explosion and fire hazards of, 549–78
  inert, effects, 361
  inhaled, retention of, 367
  injury by, anatomical factors, 362–67
    physiological factors, 367
  nuisance, 374
  particle size distribution, 201–4
    significant size, 203–4
    size-frequency, 202
  proliferative, effects, 361–62
  properties, 358–59
  pulmonary diseases, 357–411
  quartz analysis, chemical and petrographic, 205–8
    x-ray diffraction, 208–9
  relative flammability, 569, 570
  sample evaluation, 195–209
  sample record book, 28–29
  sampling, 190–95
    electrostatic precipitator, 193–94
    filtration, 194–95
    Greenburg-Smith impinger, 191
    impingement, 190–93
    konimeter, 192
    midget impinger, 192
    Owen's jet, 193
    sedimentation, 195
    thermal precipitation, 195
  weighing, 204
    correlation with counts, 204
Dust collectors, *see* Air cleaners
Dye houses, heat exposures in, 789
Dyeing, skin hazards in, 473

Dye manufacture, skin hazards in, 468, 473

E

Ear(s) (*see also* Hearing), abnormalities of, 500–1
  hearing process in, 656–57
  protection of, and speech communication, 692
  protectors, characteristics of, 689–91
  stigmata of, 482
Eardrum, decompression effects, 601
  pressure effects, 594–95
Ear plug(s), to exclude noise, not speech, 691
  maximum noise reduction from, 689–90
  medical considerations, 691
  program for, 692–93
Eating, in plant, rules for, 130–31
Educational institutions, industrial hygiene in, 6, 10, 16–17
Effective temperature, heat exposure limits, 792
Effective Temperature charts, 215–18
Ejectors, venturi, 329
Electric shock, protection from, 715–16
Electrometric method of radon measurement, 731–32
Electroplating, skin hazards in, 473
  ventilation for, 314–16
Electrostatic precipitator, comparison with impinger, 193–94
  in dust and fume sampling, 193–94
Enclosures, for noise control, 685–88
England, industrial hygiene in, 11–12
Entrainment, *see* Air cleaning
Equipment (*see also* Controls), color in, 87
  design (*see also* Anthropometric data), body measurements applicable to, 67
    human capabilities and, 83–108
    relation to human body size, 63–64
    for safety, 58–59
  standardization, 107–8
  visual displays, 83–91
Erythema, wave lengths producing, 788
Ethyl alcohol, distribution coefficient, 154
  elimination (curve), 158
Ethyl ether, distribution coefficient, 154
Evaporation, heat transfer coefficient for, 794
Evaporative cooling, 222–23, 227–28
Examination, medical record of, 21–22
Exhaust gas(es), and air pollution, 424, 428, 429, 431
  in explosion reduction, 538, 540
Exhaust hoods, 303–14, 318–19
  canopy, 311–12
  downdraft, 302, 312, 314
  face velocity, 310
  flanges and baffles, 305–6
  sidedraft or backdraft, 312–13
Exhaust systems, duct design, 329–40
  friction losses, 332–39
Exhausters, fans, blowers, 326–29
Explosion(s) (*see also* Dust, explosibility), control, butadiene, illustrated example, 540–41
    inert gas use, 575–77
    oxygen limits in, 575–77
  dust, causes, 550
    conditions necessary for, 549
    and fires, prevention, 571–78
    pressures in, 566–69
  methods of minimizing, 538–48
    adequate ventilation, 545–46
    combustible gas indicators, use of, 548
    control of oxygen content, 538–41
    elimination of ignition sources, 544–45
    operating outside flammability range, 542
    release diaphragms and vents, 546–48
    segregation, 545
    use of less flammable materials, 542–44
  relationship between combustible and oxygen, 540–41
  relief area requirements, 573–74
  static electricity in, 545
Explosion and fire hazards, dusts, 549–78
Explosion hazards, dusts, 549–58
  gases and vapors, 511–48
  of liquids, temperature effects, 536, 542, 543
Explosive concentrations, dusts, minimum, 562–64
Explosive limits, defined, 511
  dust, defined, 555
  gases and vapors, in air (table), 515–19
    in oxygen (table), 523
Explosives manufacture, skin hazards of, 473
Extremities, abnormalities of, 503–6
Eye(s), abnormalities, 496–99
  injury, infrared radiation, 719, 787
  irritation, ozone, 428
    smog, 440
    scale, 175
  stigmata, 482
Eye level, normal seated, 71–72

F

Facies, abnormalities of, 509–10
Fans, blowers and exhausters, 326–29
  laws, 328
  "man-cooling," inadequacy, 801
  selection, 327–28
Fatigue, 81, 84, 93, 98, 100, 105, 107, 111
  vibration and, 112
  vision and, 751–52, 755
Feed and cereal mills, explosion hazards, 549
Felt hat manufacture, skin hazards of, 473
Fertilizer manufacture, skin hazards of, 473–74
Fertilizer plants, explosion hazards, 549
Filament lamps, 759, 774–75
Filter life in air cleaning, 251
Filter respirators, mechanical, 347–48, 353, 354
Filters, *see* Air cleaners
Filtration, in dust sampling, 194–95
    filter-paper cups, 194
    filter-paper disks, 194
    molecular filters, 194–95
    paper thimbles, 194
Fire hazards, gases and vapors, 511–48
Fishing industry, skin abnormalities of, 490, 493
  skin hazards of, 469, 474
Flame, at reduced pressure, 591–92
Flame safety lamps, 182
Flammability, dusts, relative, 569, 570
  temperature range, 535–38
    apparatus for determining, 536–37
    combustible liquids, 538
  vapor pressure relationships, 542–43
Flammability limits, 511–23
  calculation, 514, 521–23
  factors affecting, 512
  gases and vapors, in air, 513–23, (table), 515–19
    apparatus for determining, 513–14
    in oxygen (table), 523
Flash points, determination, 535
  discussed, 532, 535
  liquids, 525–31, 538
  liquids, gases, and vapors in air, 525–31
Flaw detection, supplementary lighting for, 780–87
Flocculation, 242
Florists, skin hazards of, 474
Flour mills, explosion hazards, 549
Flue gas, in explosion prevention, 538, 540
Fluorescent lamp(s), 760, 775, 778
  spectral distribution of, 758
Fluorescent lamp industry, skin hazards of, 474
Fluorescent lighting, factors in design, 776
Fluoride fume, impinger efficiency as collector, 191
Fluorides, atmospheric concentrations, 426–27
  crop damage, 441
  damage to plants and livestock, 427
Fog, defined, 144
Food, illness due to, 128–31
    animal parasitism, 130
    bacterial poisoning, 129–30
    microbial infections, 128–29
    toxic chemicals, 130–31
Food handling, 131–32
Food sanitation, 128–34
Food vending machines, 133–34
Footcandle, defined, 745
Foot controls, 106–7
Footlambert, defined, 745
Forge shops, heat exposures in, 789
Formaldehyde, effect on skin, 490
Foundry processes, lighting for, 764–65
  noise control in, 679–80, 688
  ventilation, 313–14, 318, 320–21
Freons, in explosion prevention, 540, 544
Frequency distribution, 34
Fume(s), defined, 144
  dilution ventilation, 293–94
  entry and action, 160–61
  sampling, *see* Dusts, sampling
Fungus infections, 456, 462
Furriers, skin hazards of, 474

G

Gait, abnormalities of, 508–9
Gamma rays, exposure time to, 710
  protection from, 709–14
    employee education, 709
    medical examinations, 710–11
    personnel safety, 709–11
    pre-employment examination, 709
Garage workers, skin hazards of, 474
Gas chromatography, 190
Gases, acid, determination, 183
    effect on paint, 423
    emission to atmosphere, 424
  atmospheric, chemical activity and pressure, 591–94
    compressibility, 582–86

- Gases, (*Continued*)
    - inert, 593–94
    - partial pressures, 152–53, 586–87
    - physiological aspects, 582–91
    - solution in body, 587–89, 596–97
  - compressibility, 582–86
  - exhaust, and air pollution, 424, 428, 429, 434
    - in explosion reduction, 538, 540
  - inert, 593–94
    - in explosion control, 575–77
    - pressure effects, 599–600
  - solution in body, 587–89
- Gases and vapors, adsorption and weighing, 187
  - blood absorption curves, 157
  - body saturation, 155–57
  - collection by absorption or adsorption, 188
  - combustion devices, 185–87
  - condensation at low temperatures, 188
  - conversion table, xvi–xvii
  - defined, 144
  - distribution coefficients, 154–55
  - elimination curves, 158
  - field analysis methods, 174–84
  - fire and explosion hazards, 511–48
  - flammability, *see* Flammability limits
  - flash points in air, 525–31
  - ignition temperature, in air, 525–31
    - in air and oxygen, 532–35
  - intermittent exposures and absorption, 158–59
  - laboratory methods of analysis, 185–90
  - oxygen values and flammability, 539
  - sampling in evacuated bottles, 188–89
  - solubility, role in absorption, 153–60
  - solubility coefficient, 153–55
  - specific gravity, ventilation, 310–11
  - thermal conductivity in analysis, 190
- Gas indicators, combustible, in air analysis, 181
    - in explosion control, 548
- Gas mask, 49, 353, 354
  - canister, 343, 345–46, 353, 354
- Gas volume, temperature, pressure, water vapors effects, 152–53
- Geiger-Müller counters, shortcomings in radium detection, 729
- Genes, mutant, 698–99
- Genetic death, 698–700
- Genetic effects of radiation, 696–700
- Germany, industrial hygiene in, 13
- Germicidal lamps, 760–61
- Glass blower, emphysema of, 479–80
- Glass plants, heat exposures in, 789, 799, 800–1
- Glass workers, skin hazards of, 474
- Goggles, protective, 787–88
- Grab sampling, 47, 186–87
- Grain elevators, explosion hazards, 549
- Greenburg-Smith impinger, 191
- Grinding, ventilation, 301–3, 309, 318–19, 337
- Grip test, 98

H

- Hair, abnormalities, 491
- Hairdressers, skin hazards of, 475
- Halogenated hydrocarbons combustion apparatus, 185–87
- Handedness, and accuracy, 87–98
  - and strength, 98–99
- Hand strength, and age, 99
- Harvard School of Public Health, 6, 17
- Health physicist, duties of, 704–5
  - qualifications for supervision, 705
- Hearing, conservation of, and noise, 621–93
  - impairment and causes, 669–70
  - loss, 660
    - damage-risk criteria and, 674–75
    - frequency distribution and, 672–73
    - noise duration and, 672, 675
    - noise intensity level and, 672
    - noise susceptibility and, 673
    - noise temporal pattern and, 672
    - resulting from noise, 670–72
    - for speech, 668, 670
    - measurement of, 657–75
  - normal, 660
  - threshold, measurement of, 659–60
    - for speech, 666
    - shifts, 660
- Heat, and cancer, 469
  - control, 801–5
    - general ventilation, 804
    - in hot industries, 789–807
    - insulation, 801–2
    - local exhaust ventilation, 803–4
    - relief room in, 805
    - spot cooling, 804–5
  - effects on man, 790–91
  - exchange, *see* Air conditioning, thermal exchange
  - exposure, age and, 805–6
    - classified, 789
    - effective temperature limits, 792
    - in glass plant, 799, 800–1

      limit of endurance, 791–92
      limits fixed by thermal balance and sweat rate, 798–99
      maximum permissible sweat rate, 793–94
      maximum physiological tolerance, 793
      in mine, 799–800
      physiological limits of, 791–99
      rest periods, 807
      safe tolerance limits, 806–7
      tolerable, upper limit of, 794
      wet-bulb temperature limits, 792
  radiant, *see* Radiant heat
  removal from a space, 221–24, 227–28
  supply, 218–21, 225
  transfer, coefficients, 794
  convective, 219–20
Heat balance, *see* Thermal balance
Heat balance equation, 794
Heaters, radiant, 219–20
  unit, 220
Heat exhaustion, salt in control of, 119, 807
  susceptibility to, 807
  water and salt balance in, 807
Heat stress, flow charts, 796
    example of use, 796–97
  index, 798–99
  levels, physiological and hygienic implications, 798
  method of evaluating, 794–95, 796
  physical basis of tolerance lines, 795–98
  sweat rate as index of, 793–94
Helium, in decompression, 605
Hemoglobin, function, 149
Hoods, *see* Exhaust hoods
Hose masks, 348, 353, 354
Hot environments, physical evaluation, examples, 799–801
Hot industries, evaluating heat stress in, 794–95
  heat control in, 789–807
  supervision in, 805–6
    medical, 807
Housekeeping, 140
  in radium dial painting, 736
Human engineering, in accident prevention, 57–59, 109–10
  advance analysis, 59–63
  job analysis in, 60–63
Humidification, 224
Humidity, and explosibility of dusts, 557, 558
  and temperature, effects of, 110–11, 211–18
Hydrogen cyanide, determination, 183
  skin absorption, 162
Hydrogen fluoride, in air pollution, 426–27
  effect on vegetation, 421–22
Hydrogen sulfide, in air pollution, 416–17, 426
  detector, 184
  determination, 183–84
  effect on paint, 423, 426
  skin absorption, 162
Hypocapnia, at low pressure, 612–13
Hypoxia, at low pressure, 611–12

I

Ignition, minimum energy required for, 564–66
Ignition temperatures, 524–32
  defined, 524, 559
  dusts, 559–62
  factors affecting, 524
  gases and vapors in air and oxygen, 532–35
  gases, vapors, and liquids in air, 525–31
Illumination (*see also* Lighting), 85–86, 743–88
  defined, 745
  effectiveness in visual tasks, 747
  employee morale and performance, 773–74
  footcandle level, 746–48, 750–51, 755, 756–57
  and human efficiency, 743–44
  instruments for, 210
  production rate and, 773
  reading speed and, 747–48
  recommended levels, for industrial areas, 761
    for industrial operations (table), 762–69
  units and terms, 745
Impingement, 190–93
Impinger, comparison with electrostatic precipitator, 193–94
  Greenburg-Smith, 191
  midget, 192
  samples, counting, 196–99
Incineration, and air pollution, 424, 434
Indicator(s), combustible gas, in explosion control, 548
Indicator medium, contaminant collection in, 183–84
Industrial Hygiene Foundation, 8, 9, 53
Industrial hygiene unit, 52–53
Industrial hygienist, qualifications and training, 54–55
Industry, and industrial hygiene, 9, 11
Infrared lamps, 761
Infrared radiation, general effect, 719
  instruments for, 210

Infrared radiation (*Continued*)
  in lighting, 787
  protection, 719–20, 787
Infrared spectrometry, in gas analysis, 189–90
Insecticides, as skin irritants, 475
Institute of Inter-American Affairs, 14
Insulation, for heat control, 801–2
Insurance groups, and industrial hygiene, 8, 9, 53
Interferometer, in air analysis, 179–80
  comparison with combustion apparatus, 185–86
International Commission on Radiation Protection, 703
International Labour Office, report on European industrial hygiene, 11
Intestinal gases, in decompression, 601–2, 610
Inverse-square law, radiation protection, 709–10, 711
Ionization chamber, in radon measurement, 730, 731
  shortcomings in radium detection, 729
Ionizing radiation, instruments for, 210
Iron, in gamma ray protection, 710
  radiation protection coefficient, 717
Iron workers, skin hazards of, 475
Irritants, defined, 145
  primary, 449–51
Irritation, nasal, scale, 175
  respiratory, and air pollution, 414–18
Isoamyl alcohol, distribution coefficient, 154

J

Japan, Industrial Hygiene Association, 14
Jaundice, 487, 497
Jaw necrosis, in radium poisoning, 723
Job analysis, 60–63
  time and motion study in, 61–62
Journal of Industrial Hygiene, 6

K

Kinesthetic displays, 93
Kitchen design, 132–33
Konimeter, 192
  samples, counting, 200

L

Labor legislation, 4–5
Labor unions, and industrial hygiene, 8
Lacquerers, skin hazards of, 478
Lamps, filament, 759, 774–75
  fluorescent, 760, 775, 778
  germicidal, 760–61
  infrared, 761
  mercury, 759–60, 774–75
  spectral distribution of, 758
Larynx, 362–63
Laundries, heat exposures in, 789
Laundry workers, skin hazards of, 475
Lead, in blood, 26–27
  in gamma ray protection, 710, 711–12
  poisoning, effect on eyes, 498
    first record, 1–2
  urinary record, 24–25
Lead acetate, skin absorption, 162
Lead equivalent, defined, 716
Lead fume, impinger efficiency as collector, 191
Lead line, 502
Lead oleate, skin absorption, 162
Lead salts, skin absorption, 162
Leather tanners, skin hazards of, 475
Leg reaches, 77–78
Legislation, air pollution, 435–38
  labor, 4–5
Leucopenia, from radiation, 701, 706
  from radon, 728
Light, sources, 759–61
Lighting (*see also* Illumination), benefits of, 761–74
  brightness in, 752–55
  color in, 755
  comfort evaluation of systems, 755
  general, of industrial areas, 774–78
  infrared radiation in, 787
  luminaire selection, 774, 776
  maintenance, 778–80
  quality of, 752–55
  supplementary, 780–87
    black light, 784
    colored light, 784, 786–87
    diffuse, 780–82, 783
    directional, 780, 781
    magnification and projection, 784, 785, 786
    polarized, 784, 785
  for visibility equality, 750–51
Light output, depreciation due to lumi dirt, 779
  dirt and dust effect, 778
Limbs, abnormalities of, 503–6
  stigmata of, 482
Limits, explosive, defined, 511, 555
  gases and vapors, in air (table), 515–19
    in oxygen (table), 523
  permissible, for contaminants, 164–71
    and time element, 47
  radiation exposure (table), 703
Lips, abnormalities of, 501

Liquids, flammability, temperature range, 538
  flash points, 525–31, 538
  ignition temperatures, 525–31
  vapor equivalents of, 295–96
Lithographers, skin hazards of, 476
London air pollution disaster, 417–18
Luckiesh-Moss visibility meter, 749–50
  results obtained with, 750
Luer syringe air sampler, 184
Lumber industry, noise control in, 677, 688
Lumen, illumination, defined, 745
Luminance, defined, 745
Lung(s), cancer of, in asbestosis, 398
    and chromium, 468
    and radon, 728
  pressure effects, 595–96, 613
  rupture in decompression, 602
  structure, 147, 364
    bronchioles and alveoli, 147, 363, 365
  tissue, per cent silica in, 373

M

Machines, *see* Controls; Equipment
Machining resonant parts, noise control of, 678–79
Machinists, skin hazards of, 475
Make-up air, 225–27
  inlets for, 297
  ventilation for radioactive materials, 738
Malt houses, explosion hazards, 549
Manganese poisoning, effect on facies, 479, 509
  effect on gait, 479, 508
Masking, in hearing acuity, 664–65
Masons, skin hazards of, 472
Mass and weight, defined, 582
Mean, arithmetic, 32–33
  geometric, 33
  quadratic, 33, 34
Medical profession, and industrial hygiene, 15–17
Mercury lamps, 759–60, 774–75
  spectral distribution of, 758
Mercury poisoning, erethismus of, 480
Mercury salts, skin absorption, 162
Mesothorium, 723, 726, 739, 740, 741–42
Metabolic rate, for various activities, 795
Metal disk, use in thoron measurement, 740–41
Metal dust, explosibility, 549, 553, 554, 555, 556
Metal powders, explosive limits, 562
  ignition temperatures, 560
Metal-spraying, ventilation, 301
Methyl alcohol, blood absorption (curve), 157
  blood saturation, 156
  distribution coefficient, 154
  elimination (curve), 158
Methyl isopropyl ketone, distribution coefficient, 154
Methyl *n*-propyl ketone, distribution coefficient, 154
Meuse Valley disaster, 414–15
Microbar, sound pressure unit, 624
Microprojector, 199, 201
Midget impinger, 192
Millers, skin hazards of, 472
Mines, heat exposures in, 789, 799–800
  ventilation, 289
Mist, defined, 144
  entry and action, 161
Molecular filters, in aerosol sampling, 194–95
Mufflers, in noise control, 683–84
Munition materials, effect on skin, 487
Mutant genes, 698–99
Mutation changes, from radiation, 696–98, 699–700
Mutation rate, and lifetime radiation dose, 700
  spontaneous, 699–700

N

Nails, abnormalities, 491–92
Narcotics, defined, 146
Nasal irritation scale, 175
National Bureau of Standards, handbooks on radiation protection, list, 742
  National Radiation Committee, 704
  radioactive substances, protection rules, 735
  radium protection (table), 710
  radon standards, 730
National Committee on Radiation Protection, 713–14
National Conference of Governmental Industrial Hygienists, 6
National Fire Protection Association, safety codes, 571–78
National Safety Council, 5, 571
National Sanitation Foundation, 10
Necrosis, jaw, 723
Neutrons, fast, 721
  shielding for, 722
  thermal, 721
  tolerance dosage, 721–22
  types and effects, 720–21

Nicotine, skin absorption, 162
Nitrobenzene, skin absorption, 162
Nitrogen, absorption and elimination in the body, 588–89
  blood absorption (curve), 157
  in explosion prevention, 539–41, 557
  in fatty tissues, 597, 604
Nitroglycerin, skin absorption, 162
Nitrotoluene, skin absorption, 162
Noise (*see also* Hearing; Sound), 111–13
  air-borne, control, 647
  allowable background level in audiometry, 665
  background, and apparent hearing loss, 664–65
  band measurements of common sources, 637, 638
  control, 675–93
    damage-risk criteria, 674–75
    by ear protection, 689–93
    enclosures, 685–88
    "sandwich treatment," 679–80
    by sound-absorbing materials, 688–89
    at the source, 676–84
  elimination, impracticability of, 673
  exposure, factors in severity of, 672–73
  fundamentals of, 622–37
  hearing conservation and, 621–93
  human responses to, 656–75
  instruments for, 210
  intensity level of, 634–35
  reduction, in audiometer rooms, 666
    between two rooms (calculation, curves), 652
    example of, 653–56
  sound level values, record form, 31
Nose, abnormalities of, 499–500
  filtering mechanism for dust, 362
Nuclear reactors, thorium as fuel, 739

O

Occupation and occupational diseases, visible marks of, 479–510
Odor(s), control, 287–88
  in estimating gases and vapors, 174–78
  intensity, allyl mercaptan, 176
    commercial paraffin hydrocarbons, 177
    ethyl mercaptan, 176
    purified paraffin hydrocarbons, 178
    scale, 175
  and irritation, limitations in use, 176–77
Official agencies, 9
  chronic effects of air pollution on health, 419–20
Ointments, protective, 465–67
Opium, skin absorption, 162
Orsat, portable, in air analysis, 180–81
Osteomyelitis, in radium poisoning, 723
Owen's jet, 193
  samples, counting, 200–1
Oxalic acid, skin absorption, 162
Oxides of nitrogen, in air pollution, 424, 427–28
Oxygen, consumption, 287
  critical limit, combustion, 556
  critical values for flammability, 539
  dissociation curves of man, 592
  hypoxia at low pressure, 611–12
  limits in ignition prevention, 575–77
  partial pressure in air, 149
  poisoning, 599
  reduction in explosion prevention, 538–41
  use in ascent, 608, 614, 617
Oxygen-supplying equipment, 349–50, 353, 354
Oxyhemoglobin dissociation curve, 148
Ozone, in air pollution, 428
  eye irritation and, 428
  and hydrocarbons reaction products, 421
  rubber effects, 428

P

Painters, skin hazards of, 475–76
Paint mist, respirators, 351–52
Paint spraying, ventilation, 300
Paper dusts, explosibility, 549
Paper makers, skin hazards of, 476
Paracelsus, Philippus, 2, 443
Partial pressure(s), 152–53, 586–87
  in dry air, 152
  of water vapor, 153
Particle size, alveolar retention and, 401
  distribution, in air cleaning, 234–37
    determining, 201–4
    in diatomite processing, 403
    significant size, 203–4
    size frequency, 202
  dust and explosibility, 553–54
  of dusts, and concentrations, 359–60
  silicosis and, 374
Particulate matter (*see also* Dusts), 144, 146
  absorption, 160–61
  action, 161
Partitions, and sound transmission, 645–51
Patch tests, *see* Dermatoses, patch tests

Percentiles, 34, 68–70, 77
Performance tolerance, 108–10
Personnel, 52–55
  administrative, 54
  for audiometric programs, 668
  health physicist, 704–6
  industrial hygiene unit, 52–53
  industrial hygienist, 54–55
  qualifications and training of, 54–55
  records, 26
  sanitary engineer, 140–41
  terminology, 55
Perspiration, factor in dermatoses, 447
Petrographic determination of quartz, 205–8
Petroleum, and cancer, 468
Petroleum industry, and air pollution, 424, 426
Petroleum workers, skin hazards of, 468, 476
Phagocytes, and dust diseases, 366–67
Pharynx, 362
Phenol(s), effect on skin, 490
  skin absorption, 162
Phenolphthalein, skin markings from, 480, 486
Phonograph-record dust, explosibility, 549
Phosphorus, effect on jaw, 503
Photoengravers, skin hazards of, 476
Photographers, skin discoloration in, 488
  skin hazards of, 476
Photometric brightness, defined, 745
Photophobia, 499
Physical characteristics of environment, 210
Physiological response, standards, 162–64
Picric acid, effect on skin, 487
Pierce, John B., Laboratory of Hygiene, 8
Piping, noise control in, 683
Piston pump air sampler, 184
Pitch and resin dust, explosibility, 549
Plant location, and air pollution, 438–40
Plants as sensitizers, 451–53
Plastics dusts, explosive limits, 562
  ignition temperatures, 560–61
Pliny the Elder, 2, 343, 367
Plumbing, 121–25
  cross connection elimination, 122–24
  cross connections in, 121–22
Plywood, in noise reduction, 646, 647, 654
Plywood workers, skin hazards of, 476
Pneumatic conveying, 340
  transport velocities, 331
Pneumatic hammers, noise control of, 683
Pneumoconiosi(e)s, bauxite, 400–1
  benign, 375–76
  complicated, 407–8
  coal workers', 404–11
  defined, classified, 360–62
  diatomite, 401–4
  roentgenological classification, 406
  simple, 406–8
Poison(s), systemic, defined, 146
Poisoning, race, 484
  from radioisotopes, 722–42
Poza Rica disaster, 416–17
Precipitator(s), electric, *see* Air cleaners
  electrostatic, in dust and fume sampling, 193–94
  thermal, 195
Presbycusis, 673
Pressure (*see also* Atmospheric pressure), in air cleaner design, 233
  effects, on eardrum, 594–95
    on lungs, 595–96, 613
  partial, 152–53, 586–87
  velocity, 337
  wind, 323
Pressurized cabins, 610–11
Printers, skin hazards of, 477
Process ventilation, 299–321
Protective clothing, dermatoses, 462–64
  in radioactivity exposures, 739
Protective devices, respiratory, *see* Respiratory protective devices
Protective goggles, in infrared exposure, 787
  in ultraviolet exposure, 788
Protective ointments, dermatoses, 465–67
Psychometric chart, 793
Pulmonary dust diseases, 357–411
Pulmonary function tests for disability, 389–93
Pulmonary insufficiency, 386–88
Punch presses, noise control of, 680–81

Q

Quartile deviation, 34
Quartiles, 34
Quartz (*see also* Silica), determination, 205–9
    combined chemical and petrographic, 205–9
    x-ray diffraction, 208–9
  interference figures, 207
  x-ray diffraction patterns, 208

R

Race, factor in dermatoses, 446
  poisoning, 484
Radiant energy, 695–742

Radiant heat, distribution of, 803
  insulation for, 801–2
  shielding against, 802–3
  spot cooling and, 804–5
Radiant heaters, gas-fired, 219–20
Radiant panel heating, 219
Radiation, and heat exchange, 211–12
  in heat supply, 219
  heat transfer coefficient for, 794
Radiation, (ionizing), 210, 695–742
  corpuscular, 720–22
  exposure limits (table), 703
  genetic effects, 696–700
  infrared, *see* Infrared radiation
  injury, blood counts as index of, 706, 707
    fundamental concepts, 695–701
    in human body, 696
    latent period, 702
    symptoms and disabilities, 701
    target theory, 695–96
  lead equivalent, defined, 716
  limits for radioactive isotopes, 704
  meters, 708, 710
  neutron, *see* Neutrons
  penetrating ionizing, 701–19
    types of exposures and injuries, 701–2
  protection, National Bureau of Standards, list of handbooks, 742
  protection coefficient, defined, 716, (table) 717
  relative biological effectiveness, 703
  scattered, factor in shielding, 716
  tolerance dose, 702–4
  ultraviolet, *see* Ultraviolet radiation
Radioactive contamination, removal of, 712–13
Radioactive particles, absolute filters for, 255
Radioactive poisoning, 722–42
Radioactive sources, handling, 712
  storage, 711–12
Radioactive substances, protection, *see* Radium-dial painting, protective rules
Radioactive waste, disposal, 277, 712–14
  storage, 277
Radioactivity, control, 708–9
  detection, instruments for, 708
  units of, 707–8
Radioisotopes, 706–9
  in drinking water, 118
  precautions in handling, 708–9
  in self-luminous paint, 726
  shipping regulations, 714
Radium, and cancer, 469
  decay products, 725
  elimination rate from body, 728
  "fixed," 728
  measurement in body, 727
  poisoning, 722–39
    alpha ray effects, 726
    detection of unsafe conditions, 729–35
    injuries and symptoms, 726–27
  radioactive nature of, 724–26
  safe working distances from, 710
Radium dial painting, history, 722–24
  luminous compound used in, 726
  protective rules, 735–39
    dressing rooms and protective clothing, 739
    equipment, 737
    housekeeping and personal care, 736
    personnel selection, 735–36
    repainting dials, 738
    storage and drying of work, 737
    supervision and inspection, 736–37
    ventilation, 737–38
    wiping and pointing brushes, 736
Radon, limits, in expired air, 728
    in workroom air, 728
  as measure of radium, 725, 728, 729
  measurement, advantage of central laboratory for, 730
    comparison with standard, 730
    counting alpha particles, 730–31, 732–33
    electrometric method, 731–32
    ionization chamber in, 730, 731
    methods, 729–35
    sampling flasks for, 730, 733–35
  standards, source of, 730
Railroad workers, skin hazards of, 476–77
Ramazzini, 2–3, 411, 368, 443
Range, statistical, 32
Rats, control, 135–36
Rayon manufacture, skin hazards in, 477
Reading speed, illumination and, 747–48
Recirculation, from air cleaners, 229–30
Recompression, for decompression sickness, 617–19
Records, audiometric data, 661
  of biological specimens, 23–26
  compensation claim, 26, 28–30
  of dial painters, 728
  of environment, 21, 30–32
  health physics work, 705
  medical examination, 21–22

needed, 38–39
personnel, 26
by plant nurse, 22–23
reasons for keeping, 19–20
and reports, industrial hygiene, 19–39
survey, 51
safety, 26
training program for nurses, 23
value of, 705
Reflectance, defined, 745
Refractivity change, 179, (table) 180
Release diaphragms and vents, explosion control, 546–48
Relief area, explosive enclosure volume, 573–74
Report, industrial hygiene, 37–38
occupational disease, 20
of survey, 51
Research, needed, 38–39
Resin(s), explosion hazards, 554
manufacture, skin hazards in, 477
Respiration, 146–50
circulation factor in, 150
dead space, 147–48
hypocapnia at low pressure, 612–13
hypoxia at low pressure, 611–12
maximal breathing capacity, variations in, 391–92
mechanics, 146–47
pulmonary insufficiency, 386–88
regulation and control, 148–49
residual capacity and age, 390–91
tidal air, 147
vital capacity, 147
Respirators, abrasive-blasting, 349, 353, 354
air-line, 348–49, 353, 354, 393
chemical cartridge, 347, 353, 354
cleaning and sterilizing, 354
efficiency in paint mist, 351
examining, 354–55
gas mask, canister, 345–46, 353, 354
hose mask, 348, 353, 354
mechanical filter, 347–48, 353, 354, 393
and respiratory protective devices, 343–55
selection, 352–54
supplied-air, 348–49
U. S. Bureau of Mines, development, 343–44
tests, 344, 351–52
Respiratory irritation, and deaths from air pollution, 414–18
Respiratory protective devices, air- or oxygen-supplying, 349–50, 353, 354
types and uses, 344–52
for typical situations, 353
unapproved, 350–52, 399
U. S. Bureau of Mines, approval of, 350
Respiratory tract, diagram, 363
inhaled dust and, 362–67
Restaurant workers, skin hazards of, 477
Reynolds number, 338–39
Road makers, skin hazards of, 477–78
Roentgen, defined, 703
Roentgen-equivalent-physical, defined, 703
Roof ventilators, 324–25
Room size, ventilation requirements, 288–89
Rotary cutters, noise control of, 682–83
Rubber, in noise control, 678–80
Rubber bulb air sampler, 184
Rubber cracking test, ozone effect, 428
Rubber dust, explosibility, 549
Rubber manufacture, skin hazards in, 478
Russia, industrial hygiene in, 12–13

S

Safety, anthropology and, 63–64
environmental variables and, 108–15
equipment design and, 58–59, 83–108
errors and near accidents, 62–63
fatigue and, 59
human engineering in, 57–116
industrial design and body dimensions (*see also* Anthropometric data; Anthropometric measurements), 66–67
and industrial hygiene, 15–17
job analysis, 60–63
lighting in, 769–73
National Fire Protection Association, codes for, 571–78
noise and, 111–13
sensory warnings, auditory, 92
kinesthetic, 93
tactual, 92
visual, 83–91
severity of work and, 59
Safety Institute of America, 5
Salicylic acid, skin absorption, 162
Salt, and heat exhaustion control, 119, 807
Salts, primary irritants, 449–50
Sampling, and analysis, atmospheric contaminants, 173–210
bacteria and other microorganisms, 209–10
field record, 30–32
grab, 47, 186–87
portable rapidly indicating devices, 178–84

Sand chutes, noise control of, 680
Sanitary engineer, role in industry, 140–41
Sanitation, industrial, 117–41
Saranac Laboratories, 8
Sarcomas, osteogenic, in radium poisoning, 727
Saws, circular, noise control of, 677–78
Screw machines, noise control of, 679
Scrubbers, *see* Air cleaners, washers or scrubbers
Season, factor in dermatoses, 446–47
Seating dimensions, 78–82
  back rest, 81
  breadth, 79
  depth, 79–80
  height, 80
  shape, 80–81
  slopes of seat and back rest, 81–82
Sedgwick-Rafter cell, in dust counting, 196–97
Sedimentation, for dust sampling, 195
Sensitizers, 451–53
Separation degree, 238–40
Separators, *see* Air cleaners
Sex, factor in dermatoses, 446
Shaver's disease, *see* Bauxite pneumoconiosis
Shakeout, ventilation, 303, 309, 313–14
Shielding, neutrons, 722
  radioactive sources, 711–12
  against x-rays and gamma rays, 716–17
Shields, radiant heat control, 802–3
    absorbing, 802
    reflecting, 802
    transparent, 802–3
    water-cooled, 802
Shipbuilders, skin hazards of, 478
Shoe stores, x-ray machines in, 718
Siderosilicosis, roentgenogram, 379
Siderosis, 377–78
Silica, cristobalite in diatomite, 402–3, 404
  determination, use of Geiger counter spectrometer, 209
  industrial uses, 368, 370–71
  per cent in lung tissue, 373
  permissible concentration, 373–74
Silicosis, 367–97
  aluminum prophylaxis and therapy, 394–96
  control in industry, engineering, 393
    medical, 393–97
  criteria for diagnosis, 384–85
  defined, 369
  diatomite, 401–4
  disability evaluation, 385–93
    pulmonary function tests, 389–93
  discrete nodular, 376–77
  etiology, 369–74
  hormone therapy, 396
  individual predisposition, 374
  mixed dust reactions, 372, 377–78
  modified, 377–78
  nodular, with conglomerate lesions, 378, 380
  particle size and, 374
  pathology and x-ray examination, 376–80
  symptoms and clinical findings, 381–84
Silicotuberculosis, 380–84
  symptoms and clinical findings, 381–84
Silver, effect on eyes, 498
  effect on skin, 486
Sinuses, decompression effects, 601, 609–10
  pressure effects, 594–95
Skin, abnormalities, 486–96
  absorption of toxic materials through, 162
  cancer, 468–69
  disease, factor in dermatoses, 447
  effect of arsenic on, 487, 490, 491
  hazards (*see also* under individual industries and occupations), 471–78
  hypersensitivity, 447–48
  pallor, 486
  stigmata of, 479, 482
Smog, 413, 417, 419, 420, 421, 423, 428, 429, 434, 439–40
  defined, 144
  and total oxidants, 428
Smoke, abatement, first law in England, 413
  sampling, *see* Dusts, sampling
Solderers, skin hazards of, 478
Solubility coefficient, 153–55
Solvent(s), analysis, gas chromatography, 190
  primary irritants, 450–51
  vapor, control, 294–96
    refractivity, 180
    volume calculation, 295–96
Sonic agglomeration, 242
Sound, absorption and coefficient of, 641–43
  complex, 627–28
    time and frequency (graph), 630
  decibel, intensity level unit, 632–33
    sound pressure level unit, 636
  defined, 622
  frequency, 623, 629
  frequency analysis, 628–30
  frequency band analysis, 630–32
  intensity, 624–27, 629
    over-all, 630, 631, 632–33, 637

  intensity level(s), 634–35
    method of adding, 633, 634–35
  inverse-square law, 639–40
  isolating wall, leaks in, 650–51
  isolation, double wall in, 650
    with partitions, 645–51
    surface density of common materials, 649
  methods of recording, example, 632
  pressure level, 636
    rooms with absorbing walls, 644–45
  pure tone, 622–23
    time and frequency graph, 630
  random noise, time and frequency graph, 630
  in reverberant field, 640–41
  room with absorbing walls, 643–45
  simple source in free field, 639–40
  sources, band measurements of, 637, 638
  transmission of, 637, 639–56
  transmission from one room to another, 651–53
    noise reduction example, 653–56
  wave length, 623
Sound level values, record form, 31
Sound power, 624
  familiar sources of, 625
Sound pressure, 623–24, 626
  r.m.s. (root-mean-square), 627
  variations from complex wave, 628
Sound transmission, mass law, 648–50
Sound wave, 622
Spectrometry, in gas analysis, infrared, 189–90
    light absorption, 190
    ultraviolet, 190
Speech audiometry, 666, 668
Speech communication, criteria, 112–13
  and ear protection, 692
Speed, of work, 58–59, 62, 90, 97, 99, 102
Spice dusts, explosibility, 549
Spirography, 389–90
Spray booths, ventilation, 300
Stacks, high-temperature, 325
Standard deviation, 34–35, 68
Stannosis, roentgenogram, 379
States, industrial hygiene activities, 8, 53
Statistical analysis, 32–37
  averages, 32–33
  correlation, 35, 68, 70, 82
  data presentation, 35–37
  dispersion, 34–35
  frequency distribution, 34
  geometric mean, 33
  graphic presentation, 36–37
  mean, 32–33
  median, 33
  mode, 33
  percentiles, 34, 68–70, 77
  quadratic mean, 33
  quartile deviation, 34
  quartiles, 34
  range, 32
  standard deviation, 34–35, 68
Statistical data, uses of, 39
Steel, sheet, radiant heat control, 802
Steel-fabricating shops, noise control in, 681
Steel mills, heat exposures in, 789
Steel workers, skin hazards of, 475
Stigmata, 479
  of degeneration, 481–83
Storage vaults, for radioactive sources, 711–12
Strychnine, skin absorption, 162
Sugar refineries, explosion hazards, 549, 563
  skin hazards in, 478
Sulfur dioxide, in air pollution, 424, 425–26
  determination, 183–84
  effect on plant life, 421, 425
Sulfur dust, explosibility, 549, 563
Surface density, common materials (table), 649
Survey(s), 41–52
  harmful situation control, 48–51
    by force or persuasion, 50–51
    hygienist responsibilities, 45–46, 50–51
    improvised demonstration, 49
    recommendations, 49–51
  records of, 30–32
  records and reports, 51
  report of, 37–38
  types, 42–52
    industrial hygiene and medical, 52
    inspection, 42–43
    investigational, 44–51
    preliminary, 43–44
Survey meters, radiation, 708
Sweat rate, index of heat stress, 793–94
  thermal balance and, in heat exposure limits, 798–99

T

Tactual displays, 92–93
Tailpipe exhaust, ventilation, 316–18
Tanks, ventilation, 314–16

Temperature, in air cleaner design, 233
  Effective (charts), 215–18
  human response to, 213–14
  and humidity, effects of, 110–11, 211–18, 600
  inversion, and air pollution, 439–40
Terminal velocity, 236
Tetrachloroethane, skin absorption, 162
Textile mill, illumination, production, mending costs study, 773
Thermal balance, 791
  based on coefficients of heat transfer, 795
  limits of heat for maintaining, 794–95
  physical and physiological principles, 211–18
  sweat rate and, in heat exposure limits, 798–99
  wet-bulb temperatures for, 792
Thermal conductivity, in gas analysis, 190
Thermal exchange, *see* Air conditioning, thermal exchange
Thermal precipitator, 195
Thermal radiation, 219–20
Thermoequivalent conditions, 215
Thimbles, paper, in dust sampling, 194
Thorium, industrial uses, 739
  poisoning, 739–42
  rules for handling, 741–42
  and thoron, exposure limits, 740
Thorium mantle industry, hazards in, 739
  ventilation, 739
Thoron, measure of thorium exposure, 739–40
  methods for measurement, 740–44
    ionization chamber system, 740
    metal disk, 740–41
Threshold limit values, 165–71
Tidal air, 147
Time, factor in visibility, 745
Time and motion study, 61–62, 115
Tin salts, skin absorption, 162
Tolerance, performance, 108–10
Tolerance dose, radiation, 702–4
Toluene, skin absorption, 162
Tone, fundamental, 627
  harmonics, 627
  pure, 622–23
Tongue, abnormalities of, 501–2
Toxic materials, absorption, *See* Absorption
  entry and action, 143–71
Trachea, 363
Training and instruction, 6
Trauma, and cancer, 469
Trichloroethylene, in explosion prevention, 544
Trinitrotoluene, skin absorption, 162
Triorthocresyl phosphate, skin absorption, 162
Tripoli, *see* Silica
Tumbling barrels, noise control of, 688
Tunnels, ventilation, 289

U

Ultraviolet absorption devices, in air analysis, 182–83
Ultraviolet radiation, 787–88
  exposure, effects of, 787–88
  permissible limit, suggested, 788
  special lamps, 787
  ultraviolet meters, 210
  welding, 787, 788
Ultraviolet spectrometry, in gas analysis, 190
Uncleanliness, factor in dermatoses, 136, 447
United Automobile Workers (CIO), health institute, 8
United States, industrial hygiene in, 14, 19
United States Army, and industrial hygiene, 9
United States Bureau of Mines, dust explosibility studies, 559–60, 563
  early industrial hygiene work, 5, 6, 7
  explosion control, 540–41
  explosion pressures and rates, 566–69
  flame safety lamps, approved, 182
  flammability, determination, 513–14, 536–37
    and vapor pressure, relationship, 543
  ignition control, oxygen in, 576–77
  ignition energy requirements, 564–66
  konimeter counting technique, 192
  odor intensity (graphs), 175–78
  respirator development, 343–44
  respirator tests, 344, 351–52
  respiratory protective devices, approval of, 350
    selection outline, 354
United States Department of Labor, 5, 9
United States Navy, and industrial hygiene, 9
United States Public Health Service, diatomite industry survey, 402–4
  Division of Industrial Hygiene, 52–53
  early industrial hygiene work, 5, 6, 7
  food-handling code, 132
  particulates in city atmospheres, 429, 431–32
  pure tone threshold survey, 661
  suggested silica limit, 374
  survey forms, 32
  test for tissue response to dust, 369

  Utah mine study, 409, 410
  water and sewage methods, 117–18
Units, for air contaminants, 150–52
  illumination, 745

V

Vanadium pentoxide, effect on tongue, 501
Vapor(s) (*see also* Gases and vapors), concentrations in blood, tissue, expired air, 159–60
  defined, 144
Varnishers, skin hazards of, 478
Vegetation, damage to, *see* Air pollution
Velocity, capture, 306–9
  face, 310
Velocity pressure, 337
Vending machines, food, 133–34
Ventilation, 285–341
  abrasive-blasting, 301
  air horsepower, 328–29
  air inlets, 296–97
  air outlets, 296–98
  anemotive, 290
  capture velocity, 306–9
  codes, 340
  Dalla Valle's equation, 304–6
  degreasers, 314–15
  dilution method, 293–95
  directional, 291
  duct design, 329–40
  enclosures for processes, 299–303
  in explosion control, 545–46
  for explosion and fire control, 573–75
  face velocity, 310
  fans, 326–29
  friction losses, 332–39
  general, air-change rates, 290
    classification, 290–91
    disadvantages, 296, 298
    for heat removal, 804
    vs. local exhaust, 299
  grinding, 301–3, 309
  high-temperature stacks, 325
  hoods, 303–14, 318–19
  human requirements, 286–89
    room size effect, 288–89
  maintenance, 340–41
  make-up air, inlets for, 297
  mechanical, 290–91, 326–29
  metal-spraying, 301
  natural, 290, 322–25
  nondirectional 290–91
  odor controls, 287–89
  progressive, 298
  push-pull systems, 312–13
  radioactive materials, 737–38
    performance rating, 738
  rates, 291–93
    for local exhaust, 319
  shakeout, 303, 309, 313
  short-circuits, 298
  slot exhaust, 314–16
  solvent vapor control, 294–96
  specifications, 291–96
  specific gravity effects, 310–11
  spot cooling, heat control, 804–5
  spray booths, 300
  standard air, 328
  thermal or gravity, 290
  thorium mantle industry, 739
  velocities for control, 307–9
  welding booths, 300–1
  x-ray installations, 718
Venturi ejectors, 329
Vibration, 112–15
  subjective responses to, 114
Visibility, factors in, 745–51
  footcandle level in, 746–48, 750–51, 755, 756–57
  human element in, 755–57
  size, contrast, brightness relationships, 746
Visibility meter, 749–50
Vision, blink-rate and brightness, 753, 755
  contrast sensitivity and brightness, 753
  low pressure effects, 614
Visual acuity, as basis for lighting effectiveness, 747
  contrast in, 747
  defined, 745
Visual comfort, brightness effects, 754–55
  human element in, 755–57
Visual displays, types of, 87–88
Visual fatigue, 751–52, 755
Visual field, 83–84
Vital capacity, 147
Volume-pressure-temperature relations, 152–53

W

Warnings, sensory, 83–93
Washers, *See* Air cleaners
Waste, collection and disposal, 125–28
    sewage and other liquid, 126–27
    solid, 127–28
  disposal from air cleaners, 277

Waste (*Continued*)
  radioactive, disposal of, 712–14
Water, drinking and culinary, 118–19
  in industry, 119–20
    conservation, 120–21
    plumbing, 121–25
  radioisotopes in, 118, 704
  salinization of, 119
  source and control of, 117–18
Wax makers, skin hazards of, 478
Weighing, of dust samples, 204
Weight, defined, 582
Welders, skin hazards of, 478
Welding, ultraviolet radiation in, 787, 788
  ventilation, 300–1, 306
Wind pressures, 323
Wood planer, noise control of, 685–86
Woodworking plants, explosion hazards, 549, 559
Wrist drop, 504

X

X-ray(s), cancer and, 469
  equipment, shock protection in, 715–16
  gangrene from, 507
  unnecessary hazards from, 718–19
  protection, 714–19
    room screening, 718
  shielding of tube, 717
    lead thicknesses required, 717
  in shoe stores, 718
X-ray installations, ventilation, 718
Xylene, skin absorption, 162